NISTIR 4582

# Building and Fire Research Project Summaries 1991



U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Building and Fire Research Laboratory
Gaithersburg, MD 20899

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Noel J. Raufaste

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U.S. DEPARTMENT OF COMMERCE, Robert A. Mosbacher, *Secretary*
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
John W. Lyons, *Director*

## FOREWORD

Construction is one of the Nation's largest industries. In 1990, new construction put in place amounted to about $440 billion, more than eight percent of the U.S. Gross National Product. Costs of unwanted fires exceed $100 billion annually. The quality of constructed facilities directly affects the productivity of the U.S. building and fire community and affects the safety and quality of life of all constructed facilities. Over two-thirds of the Nation's fixed reproducible wealth is invested in the constructed facilities.

The National Institute of Standards and Technology (NIST) is recognized as the the Nation's science and engineering research laboratory. NIST develops measurement technology, testing procedures, quality assurance methods, and innovations that help build the infrastructure upon which much of the U.S. economy rests.

*About BFRL*

In early 1991, as part of an agency-wide reorganization, NIST created the Building and Fire Research Laboratory (BFRL) by merging programs from NIST's Centers for Building Technology and Fire Research. BFRL's mission is to increase the usefulness, safety, and economy of constructed facilities, and reduce the human and economic costs of unwanted fires in buildings.

BFRL's work enhances the international competitiveness of U.S. building services and products through advancements in building and fire technology. BFRL performs and supports field, laboratory, and analytical research on the performance of construction materials, components, systems and practices, and the fundamental processes underlying the initiation, propagation, and suppression of fires. The Laboratory produces technologies to predict, measure, and test the performance of construction and fire prevention and control products and practices.

BFRL's unique and comprehensive laboratory facilities include: six-degree-of-freedom structural testing facility; large-scale structural testing facility with the 53 MN (12-million pound) universal structural testing machine; environmental chambers; guarded hot-plate; calibrated hot-box; plumbing tower; building materials imaging and modeling laboratory; large burn facility for conducting experimental fires in full-scale and related combustion toxicity facility, large industrial fire test facilities, and fire suppression test facilities; and a fire simulation laboratory.

BFRL is the major nonproprietary source of technical information for development of voluntary standards by such organizations as ASTM; American Concrete Institute; American Society of Heating, Refrigerating and Air-Conditioning Engineers; American Society of Civil Engineers; Institute of Electronics and Electrical Engineers; National Fire Protection Association. The resulting standards are widely used in building codes.

BFRL works closely with its international peer organizations to maintain awareness of foreign research developments, as well as assure that generic research efforts are complementary, and U.S. interests are represented in the preparation of international standards and practices. BFRL cooperates closely with other U.S. and foreign laboratories in the conduct of its research. Eighty-one research associates from U.S. industry, guest researchers from foreign laboratories, and faculty members and students from universities worked at BFRL during 1990.

BFRL participates actively in about 200 national standardization activities; provides leadership in national and international standardization organizations and chairs more than 40 voluntary standardization activities. BFRL annually publishes over 230 reports, articles for research journals, and articles for professional and trade journals. BFRL staff annually make hundreds of presentations to professional and technical meetings of building community organizations. BFRL annually presents a series of Building Technology Symposia in cooperation with other organizations concerned with building research and practice and hosts weekly Fire Research Seminars for NIST staff and colleagues from the fire community. These are effective means of transferring the latest knowledge to practitioners, and peer researchers. The Fire Research Information Service (FIRS) consisting of national and international fire research literature and FIREDOC, the automated database of fire research literature, is the only comprehensive national library resource for the fire community.

At the beginning of 1991, BFRL had 181 employees of which 127 are professional staff, 67 have Ph Ds, and 32 are registered engineers. BFRL's budget for FY 1991 is $21 million. Congress provides $9.8 million to develop core competence in emerging research areas which will be used to assist in solving Federal agency and industry needs. The remainder, $11.2 million, is from other sources, primarily Federal agencies for solving their mission needs.

***About this Report***

This report summarizes BFRL's research for 1991. The report is arranged by its research programs: structural engineering, materials engineering, mechanical and environmental systems, fire science and engineering, and fire measurement and research. Each summary lists the project title, its research, the BFRL point of contact, sponsor, and expected results.

For further information about BFRL, its facilities, opportunities for Guest Researcher assignments, and for contracted research contact BFRL's Office of Cooperative Research Programs, Building 226, Room B226, NIST, Gaithersburg, MD 20899.

# Contents

# STRUCTURAL BEHAVIOR

# NONLINEAR/CHAOTIC BEHAVIOR OF DYNAMIC STRUCTURAL SYSTEMS

*Principal Investigator:* Emil Simiu
Structures Division
301.975.6076

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop a computational and experimental basis for the study of nonlinear and chaotic phenomena of a potential interest in structural engineering.

**PROBLEM** Engineering systems exhibiting nonlinear behavior may undergo chaotic motions. The understanding of basic aspects of such motions is needed to develop the theoretical basis of design and evaluation methods appropriate for these systems.

**APPROACH** Based on experimental data obtained from two paradigmatic nonlinear structural devices exhibiting chaotic behavior, perform basic studies aimed at improving reliability of prediction of pathological behavior for novel types of engineering structures. The two paradigmatic devices are a forced buckled column and a hydroelastic galloping oscillator. The studies focus on the effects of destabilizing noise and the relation between deterministic chaos and stochastic instability for selected types of structures.

This work leads to improved understanding of nonlinear behavior from a structural engineering point of view, and development of methods for predicting reliability of possible occurrence of undesirable structural dynamic behavior such as instabilities and jumps.

**RECENT RESULTS**

Cook, G. R. and Simiu, E., "Periodic and Chaotic Oscillation of a Modified Stoker Column," *Journal of Engineering Mechanics* ASCE (approved for publication).

Simiu, E., Cook, G. R., and Alibe, B., "Algebraic Approximation of Attractors for Galloping Oscillators," *Journal of Sound and Vibration*, (approved for publication).

Simiu, E. and Cook, G. R., "Chaotic Motions of Self-Excited Forced and Autonomous square Prisms," *Journal of Engineering Mechanics* 117, 241–259, February 1991.

Simiu, E. and Cook, G. R., "Empirical Fluidelastic Models and Chaotic Galloping: A Case Study," approved for publication in *Journal of Sound and Vibration*.

Simiu, E. and Cook, G. R., "Experimental and Numerical Chaos in Continuous Systems: Two Case Studies," *Proceedings of ASCE Mechanics Specialty Conference*, Columbus, OH, May 1991.

Cook, G. R. and Simiu, E., Periodic and Chaotic Oscillators of a Modified Stoker Column, Submitted for possible publication to *Journal of Engineering Mechanics.*

Simiu, E., Cook, G. R., and Alibe, B., "Chaotic Motions of a Hydrodynamic Oscillator and their Modeling as Diffusion Processes" submitted for possible publication in *Proceedings of Sixth International Conference on Applications of Statistics and Probability in Civil Engineering* (CERRA-ICASP6), Mexico City, June 1991.

## ASSESSMENT OF THE UNCERTAINTIES AND RISKS ASSOCIATED WITH THE DYNAMIC BEHAVIOR OF COMPLIANT OFFSHORE STRUCTURES

*Principal Investigator:* Emil Simiu
Structures Division
301.975.6076

*Sponsor:* Department of Interior
Minerals Management Service

**OBJECTIVE** To study various aspects of the dynamic behavior of compliant structures; identify and reduce uncertainties and risks associated with dynamic behavior.

**PROBLEM** Compliant offshore structures are increasingly being used in various applications, particularly in deep waters. Their hydrodynamic, dynamic and structural behavior is complex; little experience is available to draw upon to evaluate their safety performance.

**APPROACH** BFRL is investigating fundamental aspects of chaotic behavior of compliant structural assemblies subjected to fluctuating excitations of a mechanical and/or hydroelastic nature. Findings will be used by MMS to establish research needs for the reliability of compliant offshore structures and to verify reliability approaches implicit in the design of these structures. The research will assist MMS with a technical basis to ensure acceptable risks for safe operation of compliant offshore structures.

This will advance the state-of-art by making available to designers of compliant offshore platforms and other structures, methods for detecting undesirable dynamic responses.

**RECENT RESULTS** Simiu, E., "Chaotic Motion: Application to Offshore Structures," OCS Study MMS, U.S. Department of the Interior, Minerals Management Service, 1991.

## INTERNATIONAL WORKSHOP ON RELIABILITY OF OFFSHORE OPERATIONS

*Principal Investigator:* Emil Simiu
Structures Division
301.975.6076

*Sponsor:* Department of Interior
Minerals Management Service

**OBJECTIVE** To provide a forum to review methods for safety assessment applicable to offshore operations and to discuss ways of improving procedures to ensure safe operation of offshore structures in light of recent technological and regulatory experience.

**PROBLEM** A workshop on the reliability of offshore operations was held at NIST in 1985 under MMS sponsorship. In the intervening years much experience has been gained in this field. This experience must be reviewed systematically, and conclusions must be drawn from this review.

**APPROACH** Findings from a workshop held during 20–22 March 1991, will assist MMS in ensuring that risks to the public due to offshore operations are minimized.

The workshop will be used as a resource by MMS to establish research needs concerning the reliability of offshore operations.

**RECENT RESULTS** New project 1991.

## HIGH-PERFORMANCE CONCRETE

*Principal Investigators:* Nicholas J. Carino
Structures Division
301.975.6063 and

James Clifton
Materials Division
301.975.6707

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop guidelines for the formulation, evaluation, and engineering applications of high-performance concrete (HPC).

**PROBLEM** After many years of relatively slow advances in concrete technology, a worldwide awareness has arisen that the performance of concrete in areas such as ease of placement, strength development and durability can be significantly improved. This is evident from the high level of concrete research activities in Japan, Norway, and Canada. In the U.S., programs such as the Concrete and Structures program of the Strategic Highway Research Program and the establishment of the NSF Center for Advanced Cement-Based Materials are a response to the need for improved concretes. However, because these programs are either of a problem-solving nature or exploratory nature, they are unlikely, by themselves, to provide the measurement technology and design guidelines needed for U.S. leadership in HPC technology.

The most urgent research needs concern the factors affecting development of mechanical and physical properties of HPC. To meet this need, work is required to develop improved standards for evaluating the properties of HPC and to provide essential knowledge of: 1) the effects of external and internal thermal and moisture conditions on mechanical and physical properties, 2) factors affecting the elastic modulus, and 3) factors controlling time-dependent properties and deformation capacities.

High-performance concretes are concretes which achieve desirable properties outside the range of conventional concretes. Such properties include: enhanced mechanical properties, ease of placement, and long life in severe environments.

This multi-year project is aimed at advancing the understanding of the properties, the evaluation of properties, and long-term performance of HPC. The major activity of the project's first year FY 1990 was to develop an outline of a research plan intended to guide all who wish to participate in a national effort to establish U.S. competence in HPC technology. The national plan is largely based on the recommendations made at an NIST-organized workshop in May 1990.

**APPROACH** Research during FY 1991 include studies to improve the ASTM standard for compression strength testing of high-strength concrete and studies to determine the effects of temperature and moisture conditions on the development of microstructure (including microcracking) and mechanical properties of HPC. In future years, the project will be expanded to address gaps in the knowledge on relationships between selection, proportioning, and mixing of materials, the development of mechanical and physical properties, measurement of in-place properties, and the long-term performance of HPC.

The results of this work will contribute towards more widespread use of HPC and assure U.S. competence in HPC technology.

**RECENT RESULTS** Carino, N. J. and Clifton, J. R., *Outline of a National Plan on High-Performance Concrete—Report on the NIST/ACI Workshop, May 16-18, 1990*, NISTIR 4465, December 1990.

## METHODOLOGY FOR CONDITION ASSESSMENT USING NDT METHODS

*Principal Investigator:* Nicholas Carino
Structures Division
301.975.6063

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop reliable and practical nondestructive testing (NDT) procedures for condition assessment of reinforced concrete structures.

**PROBLEM** An effective plan for seismic strengthening of existing structures requires the development of material and geometric properties of critical structural elements. Nondestructive testing methods, such as ground probing radar and impact-echo, offer the potential of performing assessments rapidly compared with destructive methods, such as coring and chipping away concrete. While various techniques and devices have been developed, there are no standards for their use.

**APPROACH** BFRL is developing guidelines for applying existing testing techniques to determine material and geometrical properties of reinforced concrete structural elements and their connections. A method is being developed to use electromagnetic-wave propagation, magnetic field, and stress-wave propagation techniques in a coordinated effort to solve problems in condition assessment, including accurate determination of depth, size, and yield strength of reinforcing steel, concrete strength, and dimensions of concrete members, and accurate location of voids.

The project involves four stages:

1. Conduct a literature review of advances in electromagnetic radiation and magnetic field methods.

2. Perform controlled laboratory studies to characterize the precision and accuracy of the various measurement methods.

3. Perform testing of full-scale specimens which simulate typical structural elements and connections. Estimated concrete strengths will be compared with core strengths. This will establish the reliability of the proposed coordinated NDT approach.

4. Produce a draft guide for NDT of reinforced concrete frames.

The research results will provide the basis for the development of consensus-standards on the use of NDT methods for reinforced concrete structures.

**RECENT RESULTS** Developed methods to characterize the response of devices for locating reinforing bars in concrete.

## SHOCK WAVE ABSORBING STRUCTURES

*Principal Investigator:* Felix Yokel
Structures Division
301.975.6065

*Sponsor:* Department of Army
Construction Engineering Research Laboratory

**OBJECTIVE** To develop criteria for a structural enclosure which will attenuate the noise generated when tank artillery is fired.

**PROBLEM** Military training exercises generate considerable noise; there is a need for acoustic attenuation to reduce noise in populated areas in the vicinity of military training grounds. The noise generated by artillery is of particular concern because its acoustic frequency is in the range of 20–60 Hz where attenuation by energy absorbing materials tends to be ineffective.

**APPROACH** BFRL developed a preliminary design for a sand covered baffled tunnel structure made of corrugated steel arches. The structure, designed to accommodate a battle tank, is designed to act as a reactive muffler. Acoustic tests on a 1/200 scale model, using an electric spark as sound source yielded encouraging results.

Efforts are underway to accurately define the problem of overpressure cycles without loss of a structural enclosure and to develop energy absorbing materials. The final results from the project will enable the Armed Forces to reduce the noise from military-artillery exercises and artillery research and development.

**RECENT RESULTS** New project 1990.

# EARTHQUAKE ENGINEERING

# PERFORMANCE REQUIREMENTS FOR PASSIVE ENERGY DISSIPATION SYSTEMS FOR BUILDINGS AND LIFELINE STRUCTURES

*Principal Investigator:* Albert Lin
Structures Division
301.975.6069

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop seismic design criteria for buildings and lifeline structures incorporating passive energy dissipation systems and develop guidelines for standardized test procedures for the evaluation of passive energy dissipation devices.

**PROBLEM** The response of structures to earthquakes can be modified by using passive energy dissipation systems. One such system, the base isolation bearing, can be placed at the base of a structure to alter the period of vibration of the whole structure to reduce the lateral acceleration during earthquakes. The performance characteristics of the systems must be known before these devices can be more widely applied.

The effect of dissipators on drift, yield-and collapse-level capacity of the structure, and three-dimensional response of the structure need be established. While conventional structures are designed to codes and standards, certain existing requirements and design procedures are not appropriate for structures that incorporate passive energy dissipation systems. Design criteria for structures incorporating passive energy dissipation systems need be developed. Standardized test procedures must be developed to determine the energy dissipation characteristics of different devices.

**APPROACH** This project has three tasks:

1. Survey technical information concerning mechanical properties, hysteretic damping, aging, and long-term adhesion of elastomeric and metal surfaces.

2. Conduct parametric studies to assess the effect of dissipation systems on structural response.

3. Examine performance characteristics and applications of currently available systems.

Passive energy dissipation can be an effective method of reducing seismic hazard to existing and new buildings. This project is expected to facilitate the application of passive energy dissipation to a wider range of building and lifeline structures.

**RECENT RESULTS** New project in FY 1991.

## STRENGTHENING METHODOLOGIES FOR BRIDGE STRUCTURES

*Principal Investigator:* H. S. Lew
Structures Division
301.975.6061

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop design guidelines for strengthening bridge structures for improved seismic performance.

**PROBLEM** Recent U.S. earthquakes have established that one of the most critical aspects of lifeline security in seismic events is the inadequate performance of bridge structures. Failure of major highway concrete bridges occurred in the 1971 San Fernando earthquake, the 1987 Whittier earthquake, and the 1989 Loma Prieta earthquake. Causes of failure include: inadequate flexural ductility of columns at plastic hinges; inadequate shear strength of bent columns; bond failure in plastic hinge regions due to inadequate lapping of flexural reinforcement; and failure of bent cap/column knee joints due to high shear stress. Highway bridges designed and constructed prior to the introduction of modern seismic design requirements in the AASHTO specification (1977) need to be strengthened for improved seismic performance.

**APPROACH** The purpose of this project is to collate the available research and field-practice information, in the United States and Japan, and develop recommended guidelines for strengthening of bridge structures for improved seismic performance. This project will be carried out jointly with the University of California at San Diego. Research includes six phases:

1. Identify problem areas by examples from recent earthquakes including flexural ductility failures; flexural failures; shear failures; anchorage failures; footing failures; knee joint failures; and span collapses.

2. Develop analytical procedures for assessing critical elements and failure mechanisms.

3. Document different techniques for strengthening bridge structures that have been used in the past; including United States and Japanese experiences.

4. Document research results from the United States and Japan on methods for strengthening bridges.

5. Develop design recommendations to strengthen bridges for improved seismic performance.

6. Develop recommendations for future areas of research which have not been adequately addressed.

Two reports will be published during 1991. One report will identify failures modes of bridge superstructures and analytical procedures for assessing failure mechanisms. The second report will address the techniques used to strengthen existing bridge structures.

The results of this research are expected to produce technical guidelines for strengthening bridge structures which will improve the effectiveness of seismic retrofit strategy. Recommended procedures for improving seismic performance of bridge structures will have immediate impact on design strategies currently being developed for many seismically inadequate bridge structures throughout the United States.

**RECENT RESULTS** New project late 1990.

## TECHNICAL ASSISTANCE AND ENGINEERING EXPERTISE FOR SEISMIC CONSTRUCTION ACTIVITIES

*Principal Investigator:* H. S. Lew
Structures Division
301.975.6061

*Sponsor:* Federal Emergency Management Agency
Earthquake and Natural Hazards Program Division

**OBJECTIVE** To assist FEMA in developing improved seismic practices for new and existing buildings and lifeline structures.

**PROBLEM** Congress passed the Earthquake Hazards Reduction Act of 1977 (PL 95-124), which created the National Earthquake Hazards Reduction Program (NEHRP) in 1978. The NEHRP established the Interagency Committee on Seismic Safety in Construction (ICSSC). The Program also assigned NIST to chair the Committee to develop through cooperative activities, seismic design guidelines for existing and new buildings and lifeline systems.

**APPROACH** This project is a continuation of work with FEMA to improve seismic design and construction practices for new and existing buildings. BFRL provides the Secretariat to the ICSSC.

This work includes development of proposed "code" provisions for seismic design. These provisions are reviewed for use by codes developing organizations. Improved seismic design provisions, acceptable on a national level, are expected to lead to uniform safety and economy for all types of building construction.

BFRL works closely with the Building Seismic Safety Council (BSSC) an organization of trade associations and code groups to improve seismic design practices. BFRL provides technical assistance to the BSSC which issues seismic design provisions for new buildings (NEHRP Provisions).

The development of improved seismic design and construction practices for new and existing buildings and lifelines will save lives and significantly reduce property and economic losses during major earthquakes.

**RECENT RESULTS** Provided technical support to BSSC to prepare the 1991 edition of the NEHRP Recommended Provisions for Development of Seismic Regulations for New Buildings.

## DUCTILITY OF BRIDGE COLUMNS

*Principal Investigator:* William C. Stone
Structures Division
301.975-6075

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop rational design criteria for confining lateral reinforcement for reinforced concrete bridge columns and piers.

**PROBLEM** The 1989 Loma Prieta earthquake focused attention on the need for important highway structures and bridges to remain functional after a serious earthquake. Significant disruption of commerce, caused by collapse or partial failure of key viaducts in the San Francisco-Oakland Bay area, persisted for months following this event, compounding the direct property losses associated with the earthquake.

The current design procedures involve simplistic assumptions to arrive at a detail for the critical base region of a reinforced column used to support an elevated roadway. Arbitrary coefficients, based on gross geographic location and the "importance" of the structure are applied in most cases to achieve an equivalent static lateral force which represents the "worst case" earthquake induced lateral force amplitude.

This approach has shortcomings: a) it neglects local geology and the likely bedrock motions that can exist at a particular site; b) it neglects the effect of soil amplification as shear waves are propagated from the bedrock to the surface in regions where overburden depth is significant; c) it neglects the inelastic dynamic performance of the structure when subjected to a real-time event. In recent years several analytical tools have been developed to varying degrees that now make possible the integration of a holistic design procedure, based on fundamental physics, rather than arbitrary design coefficients. At the heart of the proposed technique is the requirement for being able to analytically track the inelastic dynamic degradation of a reinforced column. Available failure models have not yet been developed to the point where they can reliably predict apriori the behavior of a given column when subjected to a random acceleration time history.

**APPROACH** A rational design procedure will be developed in six tasks:

1. Review present design requirements for bridge piers in the United States, Japan, and New Zealand to serve as a reference to the proposed study.

2. Develop in-house analytical capability for solution of inelastic time history response of reinforced, confined concrete bridge columns subjected to both displacement and acceleration time-histories. This phase will include assessment of existing codes and determination of any required enhancements; the development of utility programs to automatically evaluate column properties; and the development of pre- and post-processing graphics programs to speed analysis and enhance interpretation of the results.

3. Develop a database of digital load-displacement histories for bridge column test specimens subjected to axial load and reverse-cycle lateral loading to be used for calibration of the analytical program.

4. Develop, based on the above two program segments, a set of hysteretic failure parameters relating the state of damage in a reinforced concrete column to the total energy absorption and maximum ductility.

5. Produce, on a demonstration basis, a rational set of site-specific bedrock acceleration-time histories (or families thereof) and apply these to a set of representative locales in the San Francisco Bay area with the objective being the assembly of a rudimentary localized contour map of site-specific design bedrock excitations. Supplemental to this, integrate a local database of soil profiles and a wave propagation routine to generate site-specific surface excitations.

6. Perform parametric studies necessary to develop design curves for bridge columns given applied loads, material properties, site details, and the degree of allowable damage following the design earthquake or earthquake series.

   This research approach will lead to a fundamental change in the manner which practicing engineers design bridge columns in seismic regions. The procedure is site specific and based on fundamental physics, rather than arbitrary design equation coefficients. It will lead to optimized (cost) design of such structures to resist a specified earthquake magnitude within a prescribed level of damage and provide, for the first time, a tool with which the local government can decide what level of damage, in quantitative terms, is to be allowed for certain earthquake magnitudes.

**RECENT RESULTS** New project in FY 1991.

## PERFORMANCE OF ELEVATED HIGHWAY STRUCTURES (VIADUCTS) DURING THE LOMA PRIETA EARTHQUAKE

*Principal Investigator:* John Gross
Structures Division
301.975.6068

*Sponsor:* Department of Interior
United States Geological Survey
Office of Earthquakes, Volcanoes, and Engineering

**OBJECTIVE** To identify causes of structural failure of elevated bridge structures resulting from the Loma Prieta earthquake.

**PROBLEM** The Loma Prieta earthquake of October 17, 1989, caused extensive damage to highway structures, particularly double-deck structures. The highway structures that failed were designed and constructed in the 1950's and early 1960's. During this period such structures were designed primarily for gravity loads; lateral resistance was checked for loads on the order of five percent of the gravity load. In addition no ductility requirements were imposed. Bridge structures designed according to such simplistic approaches are highly susceptible to severe damage and possibly total collapse under moderate ground shaking.

Identification of the collapse modes of I-880 (the Nimitz Freeway) and causes of damage to other San Francisco Bay area highway structures will identify the potential for damage or collapse of similar structures nationwide. The results of this study will also identify effective approaches to seismic strengthening.

**APPROACH** The following tasks will be performed with data provided by FHWA, AASHTO and CALTRANS on bridge designs and construction:

1. Review design documents, specifications and drawings of I-880, I-280, I-480 and 101 elevated highway structures.
2. Develop computer based analytical models (3-D FEM model) of the structures.
3. Verify the analytical models using the results of recently completed forced-vibration tests and static ultimate load tests conducted by the University of California at Berkeley.
4. Conduct dynamic analyses of the elevated highway structures.
5. Conduct parameter study to identify modes of failure of elevated highway structures and effective approaches to seismic strengthening with consideration of applicability to widely used systems.
6. Develop recommended practices for the assessment of and strengthening of elevated highway structures.

Results of the investigation will lead to recommendations for identification of collapse potential and needs for strengthening other highway structures designed and constructed similarly to those that failed.

**RECENT RESULTS** New project late 1990.

## PERFORMANCE OF PRE-EARTHQUAKE RETROFITTED BUILDINGS

*Principal Investigator:* Robert D. Dikkers
Structures Division
301.975.5863

*Sponsor:* Department of Interior
U. S. Geological Survey
Office of Earthquakes, Volcanoes, and Engineering

**OBJECTIVE** To determine the effectiveness of retrofitting methods used to strengthen existing buildings in the affected areas of the Loma Prieta and Whittier Earthquakes.

**PROBLEM** Strengthening existing buildings is one of the most effective ways to reduce hazards during earthquakes. Except for those who died due to collapse of the Nimitz Highway and one death from fire, partial or total collapse of buildings was the cause for deaths during the Loma Prieta earthquake.

Many buildings in the areas affected by the Loma Prieta earthquake were strengthened before the earthquake; some of these buildings performed well while others sustained structural damage. Due to the lack of standards for rehabilitation, many different strengthening methods are used with varying degrees of success. Information about the performance of seismically strengthened buildings is needed to 1) determine relative merits of various strengthening methods

currently being used, 2) provide performance information to practitioners for their immediate use, 3) contribute recommended practices such as FEMA's report *Techniques to Rehabilitate Existing Buildings for Improved Seismic Resistance*, and 4) define future areas of research.

**APPROACH** Because strengthened buildings are not inventoried, documentation is needed on the number, locations, and site conditions of strengthened buildings together with information on types of building (ATC 14 types of classification), types of strengthening schemes, and general descriptions of the performance of buildings. This information will be obtained from structural engineers and building departments.

For buildings believed to have been shaken substantially, detailed information on rehabilitation schemes also will be collected. This may include criteria used for rehabilitation, rationale for strengthening scheme, level of shaking (nearby strong motion records, if any), and the condition of strengthened members.

Systematic evaluation of performance of strengthening methods will be carried out and reported. This work will be done under contract by the Applied Technology Council (ATC) with NIST technical oversight. A final report by ATC will document the performance of strengthened buildings and recommendations for research and practices for strengthening existing buildings. The results of this study will aid in the development of strengthening methods for existing buildings in earthquake prone areas.

**RECENT RESULTS** New project 1990.

## MEASUREMENT OF STRUCTURAL RESPONSE CHARACTERISTICS OF FULL-SCALE BUILDINGS

*Principal Investigator:* Richard D. Marshall
Structures Division
301.975.6071

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop minimum requirements for measuring structural response characteristics of full-scale buildings.

**PROBLEM** Reliable estimates of modal frequencies, stiffness and damping of structural systems are essential to predict structural response under loading conditions associated with serviceability and structural safety. In the case of structural renovation or retrofit for hazard reduction, or for accommodating changing service loads, it is necessary that any retrofit scheme be statically and dynamically compatible with the existing structure. Although response characteristics of isolated structural components usually can be predicted with acceptable accuracy from simple models, this is not the case for complete structures where primary and secondary systems can interact in complex ways.

Numerous studies of structural response have been carried out on tall buildings, long-span bridges, and large dams. The most widely used techniques rely on ambient vibrations for excitation or, in certain cases, the use of one or more

mechanical shakers to excite specific modes of vibration. Generally, these measurements suggest a strong dependence of response parameters on displacement amplitude, thus raising questions about the validity and proper interpretation of response measurements obtained under low levels of excitation.

The recent occurrence of the Loma Prieta earthquake offers a unique opportunity to carry out a program of field measurements and analytical modeling to better understand the significance of factors such as displacement amplitude in full-scale response measurements. In particular, it should be possible to interpret measured characteristics under low-level response in the light of known high-level response.

**APPROACH**

BFRL will select undamaged buildings that were subjected to strong ground shaking and that yielded valid accelerograms during the earthquake. It should be possible from these records to obtain estimates of overall damping, the first two or three modal frequencies and the peak accelerations and displacements. These results will be compared with measured ambient and manually excited vibrations using instrumentation that is permanently installed in the structures. Modal frequencies will be identified and damping estimates from strong shaking and from ambient vibrations will be compared.

Findings from this research effort will have direct application to the improvement of analytical response models, the development of minimum requirements for obtaining full-scale response measurements, and the proper interpretation of such measurements. Structural response measurements based on a standard test method can form the basis for establishing dynamic properties of structures and may be of potential use in the evaluation of structural damage and/or remaining life.

Five buildings in the San Francisco Bay area were selected for this study; they represent a range of slenderness ratios and types of construction. Measurements of ambient vibrations in the selected buildings were completed in September 1990; the results are now being compared with the response records obtained in the Loma Prieta Earthquake. Complete test results and recommended procedures for measuring dynamic characteristics will be reported in the fall 1991.

**RECENT RESULTS**

Marshall, R. D., Phan, L. T. and Celebi, M., *Measurement of Structural Response Characteristics of Full-Scale Buildings—Selection of Structures*, NISTIR 4511, February 1991.

## EFFECT OF SUBSURFACE CONDITIONS ON SEISMIC DESIGN SPECTRA

*Principal Investigators:* Felix Y. Yokel
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301.975.6065

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE**

To examine, and if necessary make recommendations for revision of, the present NEHRP methodology used to consider the effect of site conditions on structural response to earthquakes.

**PROBLEM**

One of the prominent features of the Loma Prieta earthquake is the close correlation between the subsurface conditions and the damage pattern. While this is not a new observation (e.g., Mexico City, Caracas, etc.), it appears in this instance that even very stiff structures were damaged on sites with natural periods on the order of 0.7 s or more, while similar structures in the vicinity, resting on shallow competent soil or rock, suffered no damage. Substantial amplification of the earthquake motion was observed in areas of Bay Mud deposits (average amplification of maximum vertical and horizontal accelerations by factors of 1.8 and 2.6, respectively) and on sites of deep alluvial deposits (average amplification of maximum vertical and horizontal accelerations by factors of 1.9 and 1.8, respectively).

In the design spectra used for the equivalent lateral force procedure in present design practice it is recognized that the amplification of earthquake excitations by deep layers of soft soil will cause an increase in the base shear of structures with natural periods greater than 0.5 to 1 s. However, for shorter period structures it is generally assumed that site conditions have no effect. For deep soft soils (Soil Profiles 3 and 4 in the NEHRP recommended provisions), previous versions of the NEHRP recommended provisions actually recommended to reduce lateral design forces for short-period structures by 20%. Since stiff (low) structures are for the most part designed by equivalent lateral force procedures, rather than dynamic analysis, these latter assumptions critically affect the design and retrofit of most stiff structures.

In view of the damage observed and the substantial volume of additional information gathered in the Loma Prieta earthquake, it is important to re-examine the presently used design spectra. A realistic assessment of the effect of subsurface conditions will be of particular importance in planning, designing and prioritizing the retrofit measures required to reduce the vulnerability of existing buildings, highway structures, and lifelines.

**APPROACH**

During FY 1991 this project will focus on the modification of the bedrock motion as it is propagated through the overlying soil column and the effect of the bedrock stiffness on the response of the soil column. Research consists of four tasks: 1) compilation of accurate information on subsurface conditions in locations where ground motion records are available and bedrock motions have either been measured or can be inferred from nearby measurements; 2) selection, and if necessary modification and calibration of one or more computer programs to be used for the study in task 3 below by comparison of calculated and observed effects of subsurface conditions on ground motion; 3) examination of the effect of modifications of the ground motion, resulting from subsurface condition, on the dynamic response of structures supported at or near the ground surface, with special emphasis on short-period structures; 4) needed modification of presently used design spectra as a result from data obtained in tasks 1, 2, and 3.

The results from this project are expected to produce an accurate assessment of the effect of subsurface conditions for economical and safe design provisions and for the establishment of realistic priorities for the retrofitting of existing structures.

**RECENT RESULTS**

New Project in FY 1991

## SEISMIC RESISTANCE OF MASONRY WALLS

*Principal Investigator:* Charles Yancey
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301.975.6073

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To determine the ultimate and cracking limit states of reinforced concrete masonry shear walls.

**PROBLEM** When subjected to earthquake loads, masonry shear walls can fail in several modes: flexural failure characterized by yielding of vertical reinforcement, shear failure indicated by diagonal cracking on the faces of the walls, and combined flexural/shear modes of failure. To predict the likely mode of failure, analytical techniques are needed to calculate the flexural and shear capacities. To date, no universally acceptable formulations have been established for predicting the shear capacity of masonry walls under in-plane lateral load. Also, in lieu of expensive, time-consuming experimental programs, analytical algorithms that simulate the response of masonry walls to seismic and other loads need to be developed and calibrated.

**APPROACH** During FY 1991, BFRL will determine the ultimate and cracking limit states of reinforced concrete masonry shear walls; recommend a formula that reliably predicts the ultimate strength of fully-grouted and partially-grouted masonry shear wall designs, under in-plane lateral loads; and recommend a finite element model computer program for analytical investigations of masonry shear walls subjected to in-plane seismic loads. This effort involves four analytical tasks: 1) comparative study of existing predictive formulae for shear strength of fully-grouted, reinforced masonry walls, 2) evaluate the applicability of existing predictive formulae to partially-grouted walls, 3) analyze selected experimental walls using Finite Element Model programs to compare against experimental results, and 4) Finite Element Model analysis of a limited number of partially-grouted walls to determine the applicability of the models to this type of wall.

The results of this work will provide masonry researchers and the masonry industry with improved design recommendations to update the shear strength of masonry walls, recommended predictive formula for strength of masonry shear walls, and preliminary recommendations for the design of partially-grouted masonry shear walls.

**RECENT RESULTS** Yancey, C. W. C., Fattal, S. G., and Dikkers, R. D., *Review of Research Literature on Masonry Shear Walls*, NISTIR 4512, December 1990.

## SEISMIC PERFORMANCE OF PRECAST CONCRETE CONNECTIONS

*Principal Investigator:* Geraldine Cheok
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301.975.6074

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop technical data and recommend rational and consistent seismic design provisions for moment resistant precast concrete beam-column connections.

**PROBLEM** Strength and ductility of joints of precast concrete elements can be achieved by post-tensioning beam and column elements, special reinforcing arrangements, and fiber reinforced grout in the joints. Technical data are needed to establish provisions for codes and standards, to use precast concrete construction in seismically active areas.

There is limited guidance for designing and detailing precast concrete structures for seismically active regions. The 1985 Uniform Building Code (UBC) permits the use of precast concrete elements to resist seismic forces provided the design and detailing used satisfy the Code requirements for cast-in-place concrete structures. It is presumed that precast structures tend to be less ductile and tend to have a less stable inelastic response than cast-in-place monolithic structures. This is primarily because the inelastic strains are concentrated in the connections. Thus, the connections are often unavoidable weak links.

**APPROACH** During FY 1991, BFRL will continue performing this research in three phases. Phase 1 is the exploratory phase. Methods of improving the energy absorption characteristics is examined in Phase 2. Phase 3 involves means to improve the hysteretic behavior of the connection. A task group of researchers from academia, the research community, the Prestressed Concrete Institute, the Portland Cement Association, and the private sector, will work with BFRL staff to help guide the design of specific joint details for BFRL's consideration. An experimental model study will be carried out to characterize joint behavior. A report of the Phase 2 results is expected in the fall of 1991.

The results of the test program will be used to develop recommended guidelines for precast connections in high seismic zones.

**RECENT RESULTS** Cheok, G. S. and Lew, H. S., "Seismic Performance of 1/3-Scale Post-Tensioned Precast Beam-Column Connections," *Proceedings of the Fourth National Conference on Earthquake Engineering*, Vol. 2., 1990.

Cheok, G. S. and Lew, H. S., *Performance on 1/3-Scale Model Precast Concrete Beam Column Connections Subjected to Cyclic Inelastic Loads*, NISTIR 4433, October 1990.

# SEISMIC MONITORING OF GSA BUILDINGS

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*Sponsor:* General Services Administration
Public Buildings Service
Office of Real Property Development

**OBJECTIVE** To develop procedures and criteria for locating strong motion instrumentation in new and existing Federal buildings.

**PROBLEM** Current design criteria based on economic considerations permit controlled damage to take place in buildings during anticipated earthquake conditions. This requirement necessitates an ability to predict the resisting forces developed under large deformation cyclic loading and the likely failure mechanisms to provide safety to the building occupants. Although considerable advances have been made in mathematical modeling and dynamic analysis to predict structural performance, the accuracy of the prediction is highly dependent upon the ability to characterize the dynamic properties of the structure (mode shapes, damping) and the seismic excitation. The dynamic properties of the building can be obtained from either ambient vibration tests or low-level forced vibration tests, while site-dependent earthquake ground motions can be obtained from strong-motion instrumentation. Results obtained from these ambient vibration tests or low-level vibration tests will establish base-line response characteristics of the building to be used to determine changes in structural performance due to structural damage.

**APPROACH** Two GSA office buildings were included in this study: one in Portland, OR; the other in Los Angeles, CA. The building in Portland, OR (UBC Zone 2), is a prestressed concrete building with shearwalls providing lateral load resistance. The building in Los Angeles, CA (UBC Zone 4), is a steel moment-resisting frame structure.

The research involves five tasks:

1. Review the structural plans and specifications of the buildings; make site visits to obtain as-built building data and document structural and non-structural data.

2. Develop mathematical models for the buildings for computer analysis.

3. Perform measurements of the building's structural response to determine their dynamic properties.

4. Perform dynamic analysis of the buildings to determine their structural performance under credible earthquake excitations. The analysis identified the locations where severe damage will occur and most desirable locations for strong-motion instruments.

5. Install strong motion instrumentation in either the Portland or Los Angeles building based on the results from 4).

Detailed instrumentation schemes for the Portland and the Long Beach buildings were developed and general guidelines for strong-motion instrumentation of existing buildings were adopted by GSA.

**RECENT RESULTS** Phan, L. T., *Seismic Instrumentation of Existing Buildings*, NISTIR 4419, October 1990.

## NATIONAL ASSETS PROTECTION STANDARDS

*Principal Investigator:* Robert Dikkers
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*Sponsor:* Federal Emergency Management Agency
Office of Mobilization Preparedness

**OBJECTIVE** To develop the technical bases for developing national standards for physical security and emergency preparedness measures.

**PROBLEM** Part 1 of Executive Order 12656, November 18, 1988, requires FEMA's Director to assist the National Security Council in implementing national security emergency preparedness policy and gives the Director lead responsibility for coordinating and supporting the initiation, development, and implementation of national security emergency preparedness programs and plans among the Federal Departments and Agencies. Proposed Part 335, Title 44 Code of Federal Regulations (Federal Register, August 7, 1989), issued by FEMA, provides for the protection of essential resources and facilities which are part of the national security emergency preparedness policy and provides guidance to the Federal Departments and Agencies in its implementation.

**APPROACH** During FY 1990–1991 BFRL, working with other Federal Agencies and private sector organizations, is collecting existing guidelines, standards, and reports pertinent to this study. Based on information and discussions with officials from Federal Agencies and private sector organizations, and consultations with physical security experts and standards development organizations, BFRL is developing plans and strategies for needed physical security standards. A report will be published on the development of standards for the protection of national resources and facilities in 1991. The results of this project will assist FEMA, other government agencies, and private sector organizations plan for the physical security of assets.

**RECENT RESULTS** New project 1990.

# CONCRETE

# GUIDELINES FOR PREDICTING THE SERVICE LIFE OF CONCRETE

*Principal Investigator:* James R, Clifton
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301.975.6707

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop and demonstrate guidelines for predicting the service life of concrete structures.

**PROBLEM** Until recently, little systematic attention has been given to predicting the service life of concrete. Usually, concretes are designed on the bases of empirical relationships between materials, mixture design, and the physicochemical properties of concrete, and experience with the performance of concretes in various service environments. In most cases, concretes perform adequately. However, the importance of making quantitative and reliable life predictions in selecting concrete is now widely recognized because of 1) applications that require significantly increased service lives, 2) increased use of concrete in critical new environments, e.g., offshore, 3) the high cost of rebuilding and maintaining the nation's infrastructure, and 4) the development of high-performance concretes for which a record of performance is not available.

The increased interest in service life predictions is evidenced by: the establishment in ACI of Committee 365 on Service Life Design; service life requirements adopted for concrete to store radioactive waste; and work performed under the Strategic Highway Research Program. The recent National Materials Advisory Board publication *Concrete Durability—A Multibillion-Dollar Opportunity*, emphasized the need for long term research on concrete durability.

**APPROACH** During FY 1991, BFRL is developing a comprehensive approach for predicting the service life of a concrete structure. Included are development of mathematical models, identification of experimental investigations to obtain data needed to solve and validate models, creation of a database to provide a resource of experimental data and pertinent published data and, if necessary, development of new accelerated test methods to predict concrete performance. The durability of a concrete structure is largely dependent on the combination of 1) the composition and physicochemical properties of in-place concrete, 2) the geometry of the structure, 3) the service environment, and 4) the rate of the degradation mechanisms in different parts of the structure.

A reinforced concrete structure will be exposed to corrosive levels of chloride ions. The rates of transport or movement, reaction, and absorption of chloride ions and oxygen gas in the pores of concrete at different levels in the structure will be inputs to the models. Data on the transportation rates of chloride ions and oxygen are being obtained from BFRL's project on Transport Properties of Porous Media. Also, the effects of carbonation on corrosion will be considered. Other environmental stresses need to be considered, such as temperature and moisture. Therefore, this project will be linked to BFRL's research on Quantification of External Weathering Stresses—Measurement and Characterization of Moisture Conditions in Building Materials. It is important to have knowledge of the critical properties of in-place concrete to predict its service life. Therefore, methods and procedures to obtain and analyze field specimens are being identified.

In subsequent years a more comprehensive approach will be developed and demonstrated. Then guidelines will be prepared and submitted to voluntary consensus standard committees for possible inclusion in standard documents. The guidelines will assist in the prediction of service lives of concretes.

**RECENT RESULTS**

Clifton, J. R., "Method for Predicting Service Life," *Durability of Building Materials and Components*, pp. 361–372, 1990.

## SERVICE LIFE PREDICTIONS OF EXISTING CONCRETE MATERIALS

*Principal Investigator:* James R. Clifton
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*Sponsor:* U.S. Department of Energy
Oak Ridge National Laboratory

**OBJECTIVE**

To identify and evaluate models and accelerated aging techniques and methodologies which can be used to predict the remaining life of concrete in nuclear power plants.

**PROBLEM**

Nuclear power plants are providing about 17% of the U.S. electricity; it is expected this level will soon increase. Many of the existing plants are approaching their design life and are not being replaced with new plants. The Nuclear Regulatory Commission (NRC), and the Oak Ridge National Laboratory (ORNL) are carrying out a 5-year program to develop methods to assist NRC staff in granting life extensions to existing nuclear power plants. Concrete materials are an integral part of these nuclear power plants and consideration of any life extensions must include an in-depth assessment of the remaining safe lives of the concrete structures.

To predict the remaining service life of concrete, information is needed on 1) the condition of the concrete, 2) major environmental stresses and aging factors, 3) processes causing the deterioration, and 4) rates of deterioration. Methods for determining the condition of reinforced concrete and for identifying the causes of deterioration are being addressed in other parts of the NRC/ORNL program. Accelerated aging tests offer a means for obtaining information on deterioration rates in a reasonable time. Data from accelerated aging tests are usually inputted into either empirical or fundamental models for predicting service lives.

**APPROACH**

BFRL is performing this research as two tasks. The first task involves evaluating models for predicting the remaining service life of concrete exposed to the major environmental stresses and aging factors encountered in nuclear power facilities. An evaluation of current models which predict the life of new concrete and modifications needed to make them applicable to predicting remaining service lives of in-service concretes is being performed. Models will be evaluated based on 1) their basis e.g., theoretical, empirical, or some combination, 2) the correctness of assumptions used in their derivation, 3) the availability of data to solve them, 4) their applicability, e.g., a model may be applicable only to concrete immersed in seawater, and 5) the reliability of their predictions. The relationship between experimentally determined model inputs and the resulting predictions will be defined in terms of their qualitative effect, e.g., the effect of reducing the water-to-cement ratio of concrete on the rate of corrosion and, if possible, an estimate of

the sensitivity of predictions to the input values. If more than one model exists for a specific deterioration process, the models will be compared and recommendations prepared on which model(s) are most applicable.

The second task involves reviewing and evaluating accelerated aging tests which either provide data for service life models or which themselves can be used to predict the service lives or performance of reinforced concrete materials. Studies in which accelerated tests have lead to predictions of service lives of concretes will be reviewed and their applicability determined. Many of the standard durability tests, such as ASTM C 666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, while accelerating the degradation of concrete do not give a quantitative prediction of service life. The feasibility of using the results of such tests in making life predictions will be explored. Accelerated testing methodologies developed for making service life predictions of building materials and components, e.g,. ASTM E 632, will be evaluated with regards to predictions of remaining service lives.

The results of the project will be used in developing a reliability analysis which is required before NRC grants a life extension to a nuclear power facility. The methodology is being developed by NRC/ORNL.

**RECENT RESULTS** New project in FY 1991.

## HIGH-PERFORMANCE CONCRETE

*Principal Investigators:* Nicholas Carino
Structures Division
301.975.6063 and

James R. Clifton
Materials Division
301.975.6707

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop guidelines for formulating, evaluating, and developing engineering applications of high-performance concretes.

**PROBLEM** After many years of relatively slow advances in concrete technology, there is now a worldwide awareness that the performance of concrete can be significantly improved in areas such as ease of placement, strength development, and durability. The Concrete and Structures Program of the Strategic Highway Research Program and the recent creation of NSF's Center for Advanced Cement-Based Materials are responding to the need for improved concrete. U.S. leadership in high-performance concrete technology can be a major contributor to enhancement of the competitiveness of the nation's construction industry. High-performance concrete may be defined as concretes which achieve desirable properties outside the range of conventional concretes.

During FY 1990, BFRL developed and published a national plan. The national plan is largely based on recommendations from a BFRL-organized workshop cosponsored by ACI. The most urgent research needs identified concern the factors affecting development of mechanical and physical properties of high

performance concrete. To meet this need, work is required to: 1) develop standards for compressive strength testing; 2) provide essential knowledge of the effects of external and internal thermal and moisture conditions on mechanical and physical properties, e.g., factors affecting the elastic modulus, factors controlling time-dependent properties and deformation capacities; and 3) develop measurement methods of in-place properties of high-performance concrete.

**APPROACH** Research during FY 1991 includes developing information on specimen size effects and the causes of such effects, evaluating requirements for initial curing, and determining the influence of testing machine variables. Research will determine the effects of temperature and moisture conditions on the development of microstructure (including microcracking) and mechanical properties, variation of microstructure and mechanical properties through concrete specimens of different dimensions, and studies of the effects of curing conditions on long-term performance. Models to predict moisture movement through low-porosity concrete are being developed to study the effect of moisture conditions on curing. In future years, the project will be expanded to address gaps in the knowledge on relationships between selection, proportioning, and mixing of materials, the development of mechanical and physical properties, measurement of in-place properties and the long-term performance of high-performance concrete.

By the end of FY 1991 research is expected to produce an experimental design for studying effects of moisture and temperature on curing of high-performance concrete; a synthesis of previous research on effects of specimen preparation and specimen size on compressive strength; reports on the effects of internal and external temperatures during cure on microstructure development and on methods to improve compressive strength test for high-performance concrete.

**RECENT RESULTS** Carino N. and Clifton J., *Outline of a National Plan on High-Performance Concrete Report on the NIST/ACI Workshop, May 16-18, 1990*, NISTIR 4465, December 1990.

## COMPUTER SIMULATION OF TRANSPORT PROPERTIES OF CEMENTITIOUS MATERIALS

***Principal Investigator:*** Edward J. Garboczi
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***Sponsor:*** National Science Foundation
Center for Advanced Cement-Based Materials
Northwestern University

**OBJECTIVE** To develop models for predicting transport properties of cementitious materials.

**PROBLEM** The digital-image-based microstructural simulation model for cement paste developed by BFRL in the last two years is an important departure from previous models developed by cement researchers; it uses digital images to represent cement particles and their hydration products. The model uses simple but realistic growth rules that incorporate elements of randomness. These growth rules, when iterated many times, result in microstructures that agree favorably with real cement pastes. This agreement is not only visual and qualitative, but is also quantitative in the areas of percolation properties and capillary pore diffusivity.

The Fogelholm transport algorithm has been used to compute the diffusivity of the capillary pore space of the microstructural model, which is in good agreement with experiment. The lattice structure imposed by the digital image representation enable this sophisticated algorithm to be employed. Incorporating the diffusivity of the microporous C-S-H phase will permit the further testing of theoretical concepts about the transport properties of the pore space of cement and concrete. The diffusivity of concrete plays a key role in material degradation processes. To analyze the diffusivity of the C-S-H phase, a new transport algorithm is needed, one that can handle more highly connected structures than can the Fogelholm algorithm.

**APPROACH**

BFRL's research is based on combining the microstructural model with a conjugate gradient relaxation algorithm that was made available to BFRL by Professor P.M. Duxbury of Michigan State University, Physics and Astronomy Department. This algorithm will enable direct, accurate computations of the pore space diffusivity of the BFRL model to be carried out. As the diffusivity of cement and concrete plays an important role in determining their susceptibility to attack by environmental species, there is a great deal to be learned by directly simulating this process on the model and studying it as a function of extent of hydration, initial particle-size distribution, and water-to-cement ratio. Unlike the Fogelholm algorithm, the conjugate gradient method also gives local flow information. Also, the local flow around aggregate particles will be studied to determine the effect of the highly porous interfacial zone on transport in concrete. Results from this work will then be used to study the diffusivity of mortar, since the interfacial zone flow will be able to be treated realistically.

This research is in collaboration with Professor Hamlin Jennings of Northwestern University through the NSF Center for Advanced Cement-Based Materials. A graduate student from Northwestern University will work at BFRL during the summer of 1991.

**RECENT RESULTS**

Garboczi, Edward J. and Bentz, Dale P., "Computer Simulation of the Diffusivity of Cement-Based Materials," *Journal of Materials Science*, 1991.

Garboczi, Edward J. and Bentz, Dale P., "Digital Simulation of the Aggregate Cement Paste Interfacial Zone in Concrete," *Journal of Materials Research*, Vol. 6, pp. 196, 1991.

"Simulation Studies of the Effects of Mineral Admixture on the Cement Paste-Aggregate Interfacial Zone," *ACI Materials Journal*, 1991.

## KATZ-THOMPSON PERMEABILITY THEORY APPLIED TO CEMENT PASTE, MORTAR, AND CONCRETE

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*Sponsor:* National Science Foundation
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Northwestern University

**OBJECTIVE**

To systematically check the validity of the Katz-Thompson permeability theory for cement paste, mortar, and concrete.

**PROBLEM** The permeability of cement-based materials to fluid flow, under an applied pressure gradient according to Darcy's Law, is a theoretically well-characterized measurement, which has great importance in determining various performance criteria and long-term service-life. However, the relation of this quantity to microstructural parameters is essentially uncharacterized.

Katz and Thompson, researchers at Exxon Production Research Company, developed a percolation theory-based-equation for predicting fluid permeability, as a function of microstructural parameters that are measurable by a mercury porosimeter. The key parameter is the critical pore diameter, $d_c$, at which the pressurized mercury first forms a continuous pathway through the intruded sample. This equation has been well-verified for sandstone and carbonate sedimentary rocks, and there is some evidence that the equation will work well for cement paste.

**APPROACH** The work is being performed in collaboration with Professor Douglas Winslow of the Purdue University Civil Engineering Department. This 2-year project will develop the definition of $d_c$ for mortars and concrete, and the appropriate pretreatment of cement-based material for valid permeability measurements. Samples will be made at Purdue. A permeability apparatus is being constructed at BFRL to make the transport measurements. The mercury permeability measurements are being performed at Purdue University. The Katz-Thompson theoretical analysis is being done at BFRL. Mortar is being studied during FY 1991; cement paste and concrete will be studied in FY 1992.

BFRL is systematically checking the validity of the Katz-Thompson permeability theory for cement paste, mortar, and concrete. If the result is positive, then for the first time there will be available a mathematically rigorous, physically sound way to relate significant, measurable microstructural parameters to the fluid permeability of cement-based materials. The Katz-Thompson equation offers the possibility, for the first time, of quantitatively relating the fluid permeability of cement-based materials to their microstructure.

**RECENT RESULTS** Constructed and successfully tested a Nitrogen Permeability apparatus.

Performed SEM analysis of interfacial zone region in model mortars.

## TRANSPORT PROPERTIES OF POROUS MEDIA

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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop and apply analytical and computer simulation models of the transport of fluid and ions in the pore space of porous materials like hardened cement paste and concrete to the problem of service life.

**PROBLEM** The basic understanding of the mechanisms of degradation is crucial to developing a valid scientific basis for service life prediction. An essential physical (as opposed to chemical) mechanism in almost all such processes is the penetration of external species (fluids) into microstructural elements, which allows

deleterious reactions to take place. An example is the diffusion of $Cl^-$ ions through water-filled pores in reinforced concrete to the steel reinforcing bars. When a high enough concentration of ions is achieved, corrosion of the bars can begin. Also, degradation of concrete under freezing and thawing conditions depends on the movement of water in the pore/void structure of the material.

**APPROACH**

Research in FY 1991 concentrates on exploiting the digital-image-based cement paste microstructural model developed in FY 1990 to study important material questions, and further develop transport algorithms. The model provided a powerful tool to investigate the effect on microstructure of various kinds of reactive and nonreactive fillers, and the resulting effect on transport properties.

The model will be used to study the percolation properties of cement paste models with reactive (e.g., silica fume) and nonreactive (e.g., carbon black) fillers. The percolation properties are an important measure of the effect of fillers on pore and solid structure. The effect, on the interfacial zone around aggregate particles in concrete, of such fillers are being studied. The effect on diffusive flow of interfacial zones will be studied.

Fluid flow through a porous material can be directly simulated via finite-difference methods. An algorithm to do this for the digital-image-based microstructural model will be developed, and tested on simple models where mercury injection and electrical conductivity will be simultaneously simulated to further validate Katz-Thompson permeability theory.

Diffusivity of the pore space in cement paste can now be routinely simulated, based on FY 1990 work. This algorithm, in conjunction with a method to be developed to dissolve calcium hydroxide (CH) in the microstructural model, will be used to study how the diffusivity of cement paste changes as CH is leached. A "calibration curve" will be generated, showing diffusivity versus fraction of CH remaining, which will be of use to those modelling the kinetics of the leaching process.

The connectivity of the pore space in cement-based materials basically determines the transport properties, which in turn determines the service life. Relating transport properties like fluid permeability and chloride diffusivity to material parameters is then crucial in order to be able to predict service life.

This project will address the key question of how rates of transport of fluids and ionic species in cementitious materials are related to pore structure, and ultimately service life. The knowledge gained from this study will contribute to a better understanding of the mechanisms of degradation processes in concrete and other porous materials and thus help establish the scientific basis for service-life prediction standards.

**RECENT RESULTS**

Bentz, D. P. and Garboczi, E. J., "Percolation of Phases in a Three-Dimensional Cement Paste Microstructural Model," *Cement and Concrete Research*, Vol. 21, pp. 325–344, March/April, 1991.

Bentz, D. P. and Garboczi, E. J., *Modeling the Leaching of Calcium Hydroxide from Cement Paste—Effects on Pore Space Percolation and Diffusivity* (manuscript in review).

# PERFORMANCE CRITERIA FOR LONG LIVED CONCRETE FOR RADIOACTIVE WASTE STORAGE

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*Sponsor:* Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Division of Engineering

**OBJECTIVE:** To develop performance criteria for selecting concretes for constructing structures with 500 year safe lives for storing low-level radioactive wastes.

**PROBLEM:** The U.S. Nuclear Regulatory Commission (NRC) is responsible for developing a strategy for storing low-level radioactive wastes. According to one approach, the radioactive wastes would be stored in concrete vaults buried in the earth or constructed above ground and covered with earth. A safe service life of 500 years is required for the storage vaults.

Several observations suggest certain concretes could have average service lives of 500 years. Remnants of some concrete structures constructed during The Roman Age are still intact. These concretes may not be representative of the typical concrete of their era and statistically only a minute sample of the population, e.g., one concrete structure out of a thousand or so survive. Further, ancient concretes contain cements of significantly different compositions than modern cements. Predictions suggest a high quality concrete could have an average service life exceeding 1000 years if the exposure conditions were not severe. This prediction, however, is based on the properties of unaged concrete and does not consider that the properties of concrete could degrade with time.

The first phase of this work was performed in 1987. It identified likely deterioration processes. The processes include sulfate attack, corrosion of reinforcing steel, alkali-aggregate reactions, leaching by groundwater, and acid attack. A significant cause of premature concrete failure is not anticipating the full range of environments to which a concrete may be exposed. The likely deterioration processes have been analyzed in terms of the existing knowledge of their mechanisms, rates, and characteristics of their deterioration curves. In 1988, BFRL developed an experimental approach to obtain data needed to make service life predictions, identified candidate concretes and obtained the concrete materials, and undertook modelling of moisture transfer processes in concrete.

In 1989, development of models of transport processes in concrete involving the rate of moisture, chloride ion, and sulfate ion movement in concrete was completed. Experimental studies were carried out on the chloride ion diffusion coefficients in cement pastes. In 1990, a new test method for determining the potential alkali reactivity of siliceous aggregates was investigated. This work also included the development of an accelerated test for studying the sulfate attack of cementitious materials.

**APPROACH** In this multi-year project, the development of performance criteria will involve many of the steps included in ASTM E 632, "Standard Practice for Developing Accelerated Tests to Aid Predictions of the Service Life of Building Components and Materials." Accelerated testing with mathematical modeling of the rate of deterioration of concrete will be used in making the service life predictions.

Essential aspects of developing accelerated tests and mathematical models include the identification of expected exposure conditions, identification of potential deterioration processes, and development of relationships between the properties and uniformity of concrete and its resistance to the expected deterioration processes.

During FY 1991, investigations are being conducted on the effect of temperature on the rate of reaction. The studies on sulfate attack will be continued. Also, recommendations of additional needed research will be explored and a research plan to address them submitted to the Nuclear Regulatory Commission. The results of this research are expected to produce performance criteria to assist in the selection of concrete materials and methods to predict service lives of concretes.

**RECENT RESULTS**

Clifton, J. R. and Knab, L. I., *Selection of Siliceous Aggregate for Concrete*, NISTIR 4327, June 1990.

Pommersheim, J. M. and Clifton, J. R., *Model of Transport Process in Concrete*, NISTIR 4405, September 1990.

## CHARACTERIZATION OF THREE PORTLAND CEMENT CLINKER REFERENCE MATERIALS BY X-RAY POWDER DIFFRACTION

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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE**

To obtain and analyze data, based on x-ray powder diffractometry, on the phase abundance, intra-, and intersample homogeneity for three NIST cement clinker Reference Materials (RMs).

**PROBLEM**

Three sets of portland cement clinker samples were made available by NIST's Standard Reference Materials Program (SRMP) as Reference Materials. The intended use of these RMs is to develop and test methods for the quantitative phase abundance analysis of cement clinker by optical microscopy and x-ray powder diffraction.

X-ray powder diffraction (XRD) is a bulk analysis method for the identification of phases in a powdered mixture and, with calibration curves, the determination of phase concentrations. Using calibration curves developed with an automated powder diffractometer, phase abundance analyses can be performed on randomly selected samples of the SRMP clinkers. The data is used for to evaluate the intra- and inter-sample homogeneity permitting the reclassification of the clinkers from Reference Materials to Standard Reference Materials.

**APPROACH**

The project is divided into two tasks: 1) the random selection of clinker samples and 2) qualitative and quantitative analysis of the major and minor phases. Eight samples from each clinker will be selected using a random stratified sampling plan. Based on recommendations of the SRMP statistician, the first and last samples from each RM will be force-selected. The eight samples will be split to provide two replicates. Each replicate will be subdivided for major and minor phase analysis, with each subreplicate being analyzed in duplicate.

Clinker will be ground to an optimum particle size (1 to 10μm) for quantitative x-ray analysis and blended with NIST SRM 640, silicon powder, as an internal standard. Each powder replicate subsample (major and minor phase) will be analyzed in duplicate under the same instrumental conditions as the calibration mixtures. Statistical analysis of the x-ray data for homogeneity and certification of phases will be performed by SRMP.

The results of this research will form a basis for upgrading the clinker RMs to Standard Reference Materials. Certification of phase abundance will provide the very first set of Standard Reference Materials for portland cement clinkers. Their intended use is in the development and testing of techniques for quantitative phase abundance analysis.

**RECENT RESULTS** New project in FY 1991.

## CEMENTITIOUS MATERIALS MODELING LABORATORY

*Principal Investigator:* James R. Clifton
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301.975.6707

*Sponsor:* National Science Foundation
Center for Advanced Cement-Based Materials,
Northwestern University

**OBJECTIVE** To centrally archive models developed by the Center for Advanced Cement-Based Materials and those pertinent to the research of the Center; develop guidelines and protocols for development and documentation of models to facilitate their interfacing and use; and coordinate interfacing the models.

**PROBLEM** The Center for Advanced Cement-Based Materials (ACBM) was created in February 1989 under the sponsorship of the National Science Foundation. Modeling is a significant component of each major area of the Center's investigations; it is a way of coordinating ACBM's research and facilitating its engineering applications. Micromodels, developed to describe individual phenomena, will be linked to form macromodels. The macromodels will either be formed by linking micromodels developed by the Center's researchers or by linking existing micromodels. In addition to serving the Center's researchers, the models will be effective tools for transferring the knowledge and technology generated by ACBM to other scientific and technical communities and institutions. Related BFRL projects funded through the Center, "Computer Simulation of Transport Properties of Cementitious Materials," and "Katz-Thompson Permeability Theory Applied to Cement Paste, Mortar, and Concrete" will be linked with the modeling laboratory.

**APPROACH** This project involves collaboration between the BFRL and modelers at Northwestern University, University of Illinois, Purdue University, and Michigan State University. BFRL is working with the other members in archiving and maintaining model software and documentation.

A mathematical modeling workshop has been established to familiarize graduate students in the ACBM Center on the application of modeling techniques to predicting the properties and performance of cement-based materials. The second workshop will be held in the summer of 1991.

The results of this work are expected to produce guidelines for developing mathematical models to assist researchers interested in the application of models.

**RECENT RESULTS**

Kaetzel, L. J. and Clifton, J. R., *Guide to the Use of the Cement and Concrete Research Remote Bulletin Board System (RBBS) Computer*, NISTIR 4473, December 1990.

# COATINGS

# MODELS OF THE DEGRADATION OF ORGANIC PROTECTIVE COATING SYSTEMS

*Principal Investigator:* Tinh Nguyen
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301.975.6718

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop mathematical models for blistering and corrosion of steel under intact high performance coatings and develop a method for quantitatively determining the thickness of the water layer at the interface between the coating and the steel surface.

**PROBLEM** Corrosion-related problems in the United States are estimated to cost $220 billion annually (4.2% of GNP). The use of polymeric coatings is an effective, economical, and widely-used means to prolong the life of corrosion-prone construction materials. However, coatings are susceptible to degradation under in-service environments. Surface analysis data indicate that changes at the substrate/coating interface are often responsible for the failure of coatings. Interfacial changes can lead to the formation and growth of blisters and to the occurrence of corrosion reactions beneath protective coatings. Since blistering and corrosion beneath coatings are important mechanisms of degradation, research is needed to better understand the degradation mechanisms and transport phenomena through the coating and along the coating/metal interface, and support the development of mathematical models for predicting the service life of coating systems. The models are needed to provide the bases for improved standards for coatings used to protect steel structures.

**APPROACH** Research in FY 1991 concentrates on 1) developing a conceptual model for blistering and corrosion of steel under high performance, intact coatings, 2) carrying out experiments to verify the mechanisms of blister and corrosion of steel under intact coatings, 3) developing mathematical models for quantitatively describing the blistering and corrosion processes on steel under intact coatings, and 4) quantifying water at the interface between a coating and the steel surface. Although BFRL researchers were successful in developing a method to measure in situ water at the interface between a thick, opaque coating and a high reflective metal in 1990, they were not able to quantify water at the interface between a coating and a steel substrate due to the poor reflectivity of steel. A portion of 1991 will be spent addressing this effort.

During this year BFRL researchers expect to develop papers on "Mathematical Modeling of the Transports of Corrosive Elements Through Intact High Performance Coatings that are Responsible for Blistering and Corrosion of Coated Steel" and on "Quantitation of Water at the Interface Between Coatings and Steel Surface"; and develop a plan for and organize a workshop on the development and uses of mathematical models in practical applications and standards for building and construction materials.

BFRL will expeditiously transfer the results of this work to the standards and industrial communities resulting in a strong scientific and technical basis for standards for high-performance coatings for steel used in buildings and other construction.

**RECENT RESULTS**

Nguyen, T., Byrd, E., Lin, C., and Bentz, D., "A Novel Spectroscopic Method for the In-Situ Studies of Water at the Interface between a Metal and an Opaque Polymeric Film"; *Proceedings of the Symposium on Composites, Processing, Microstructure and Properties*, 1991.

Bentz, D. and Nguyen, T., "Simulation of Diffusion in Pigmented Coatings on Metals Using Monte-Carlo Methods," *J. Coatings Technology*, Vol. 62, April 1990.

Nguyen, T. and Lin, C., "In Situ Measurements of Chloride at the Coating/Metal Interface," *Journal of Adhesion*, 1991.

Nguyen, T., Hubbard, J., and McFadden, G., "A Mathematical Model for the Cathodic Blistering of Organic Coatings on Steel Immersed in Electrolytes," *J. of Coatings Technology*, March 1991.

Nguyen, T., Byrd, E., and Lin, C., "A Spectroscopic Technique for In-situ Measurement of Water at the Coating/Metal Interface," *J. Adhesion Science and Technology*, 1991.

## QUANTIFICATION OF EXTERNAL WEATHERING STRESSES

*Principal Investigator:* Jonathan W. Martin
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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE**

To 1) demonstrate a method for characterizing the environment for materials, 2) develop methods for quantitatively characterizing the periodicities and statistical fluctuation in the factors comprising an exposure environment, 3) demonstrate how these measurements can be made on coated steel structures, 4) transfer this knowledge to the building community, and 5) demonstrate how this technology will aid in predicting the service life of a variety of building materials.

**PROBLEM**

Over the last ten years, revolutionary changes occurred in the compounding and formulating of many building materials. These changes were initiated by legislative mandates and by higher performance requirements demanded from engineers and designers. Legislation driven changes include hazardous chemicals and volatile organic contents; performance-driven changes include the need to reformulate concrete to meet higher strength or sulfate-resistance requirements. Although most materials satisfy the initial properties of an acceptable material, methods for collecting long-time performance data in a timely manner are unavailable. A need exists for methods which are capable of accelerating the degradation of building materials without changing the dominant failure mechanism(s) while providing data which would be useful as input for predicting the service life of a material in its intended operating environment.

Quantification of individual weathering factors is an essential element in NIST's long term strategy to advance the technology of service life prediction. Needed are better knowledge of material degradation processes and better characterization of the environments to which these materials are exposed. A framework

needs to be established for identifying key gaps in knowledge and for providing the starting point for filling in these gaps.

In FY 90, BFRL's research efforts were coordinated with: two of the leading commercial outdoor exposure facilities; the ASTM Committee G 03 on "Durability of Nonmetallic Materials," and NOAA and other researchers collecting meteorological data. BFRL's laboratory research focused on the development of improved methods for measuring the time-of-wetness of building materials as a way of overcoming the shortcomings of the currently available time-of-wetness devices.

**APPROACH** In FY 1991, BFRL's research is proceeding in two directions. First, time-of-wetness measurements will be transferred into the field for identifying potential technical and nontechnical problems. Second, BFRL will analyze several large ultraviolet radiation (UV-radiation) data sets collected by NOAA and the Smithsonian Institute. The research will be coordinated with NOAA, privately owned exposure sites, and industry through direct contact and ASTM and RILEM/CIB activities. The analyses are expected to determine differences in the periodicities of UV-radiation at the same site, but in different years, and between sites, but over the same time period. BFRL will 1) instrument steel structure with moisture sensors, 2) prepare a report on recommendations for a standard on characterizing external weathering factors, 3) author a paper on characterizing the periodicities of moisture and UV-radiation at different sites and at different times, and 4) chair a RILEM/CIB Task Group on Environmental Characterization.

**RECENT RESULTS** "Sorption of moisture on epoxy and alkyd free films and coated steel panels," *Journal of Coatings Technology* presented at the Federation of Coatings Meeting in October 1990.

## SCREENING FOR LEAD IN PAINT USING SPOT TESTS

*Principal Investigator:* Mary E. McKnight
Building Materials Division
301.975.6714

*Sponsor:* Department of Housing and Urban Development
Innovative Technology and Special Projects Division

**OBJECTIVE** To investigate the sensitivity and accuracy of spot tests for lead in paint films.

**PROBLEM** As a result of recent legislative and regulatory actions, there is a need for a quick, inexpensive test to detect lead in existing paint films in housing. Results of recent studies on the use of spot tests have been mixed. Since a screening test would be useful to many public housing agencies and other groups, additional work focusing on procedure modifications, chemicals used, and training of operators is needed.

**APPROACH** BFRL's research will be carried out in two phases. In the first, laboratory experiments will be conducted to further understand important variables in spot tests, including pigment type, dissolution or leaching method and spot test reagent. Based on these results a preliminary spot test procedure will be developed. Using

the preliminary procedure, laboratory tests will be conducted on laboratory prepared samples and field samples to evaluate the precision and accuracy of the procedure. In the second phase, the study will move to the field where trained testers will carry out the modified procedure to determine the accuracy and precision of the test procedure.

**RECENT RESULTS** New project 1991.

## ORGANIC COATINGS

*Principal Investigator:* Mary McKnight
Building Materials Division
301.975.6714

*Sponsors:* Tri-Services Facilities Coatings Committee
U.S. Army, Engineering Housing Services Center
U.S. Navy, Naval Facilities Engineering Command
U.S. Air Force, Air Force Engineering and Services Center

**OBJECTIVE** To develop improved procedures for selecting, using, and specifying coating systems and transferring the technology to DoD.

**PROBLEM** The annual cost associated with using organic coatings in the United States exceeds $10 billion; more than half comes from using protective coatings in buildings and structures. For military facilities (estimated $300 billion real property value), the annual cost of coating maintenance is about $400 million. If effective criteria for the selection, specification, and use of protective coatings were available, as much as 25% of these expenditures could be saved. An essential element of selection and use criteria for protective coatings is service life.

**APPROACH** During FY 1991 BFRL will draft a charter for consideration by the Federal Agencies Committee on Coatings for Facilities; serve as chairman of the ASTM D01.07 committee on government relations, with the committee's attention being directed towards a review of DoD test-method needs and appropriate actions recommended; serve as chairman of the SSPC coatings steering committee and coordinate the development of SSPC specifications for low VOC coatings; provide appropriate technical and organizational support to develop a Tri-Service guide specification for painting facilities; and update the Tri-Service Protective Coating Manual.

Much of this work will be accomplished by visiting military installations and attending coatings meetings to learn of existing and potential problems; broaden the base of the Tri-Service committee meetings to include other Federal agencies for improving technology transfer among government agencies; carry out laboratory studies to develop improved test procedures relevant to the field problems; provide leadership in standards activities to focus attention on DoD problems; and implement the results of the work by writing manuals, presenting talks, and publishing reports.

**RECENT RESULTS** Draft a guide specification for painting facilities for review by the Tri-Services.

# ROOFING

## PERFORMANCE CRITERIA FOR SINGLE-PLY ROOFING MEMBRANES

*Principal Investigator:* Walter J. Rossiter
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301.975.6719

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop draft performance criteria for seams of single-ply membrane materials.

**PROBLEM** Use of single-ply roofing membrane materials account for about two-thirds of the low-slope membrane systems annually installed in the United States. Many factors have influenced the rapid acceptance of these roofing membranes; durability, performance, cost, and architectural considerations. In spite of their acceptance, the system's performance has not been problem-free. Survey information from the National Roofing Contractors Association (NRCA) indicate performance problems have been more prevalent for the single-ply systems than for built-up systems. Of the problems described in the NRCA surveys, defective laps and seams are the most frequent citations, accounting for about 24 percent of those reported. In the 1987 NIST/NRCA Round Table on Roofing Research report, it was stated that, "the factors affecting roofing performance must be more fully understood to assure success with new materials and systems," and that performance tests and criteria for single-ply systems need to be developed.

**APPROACH** Research in FY 1991 will focus on developing performance criteria for seams in single-ply systems. Requirements will address adhesion, water permeability, puncture resistance, and durability. Development of criteria and test methods will be based on observations of failures in the field, calculations of stresses using mathematical models, laboratory test results, and existing U.S. and foreign information on roof membrane performance. Investigations on the effects of ponded water and ozone on the creep-rupture of seam joints stressed in tension and shear will be conducted. The performance criteria and test methods will be presented to the ASTM task group on seam performance for review and critique.

Expected progress for 1991 includes: conducting the 3rd International Symposium on Roofing Technology, April, 1991; developing a draft performance criteria for seams of single-ply membranes; present draft performance criteria to ASTM's Committee D08.18 Seam Performance; and chair the RILEM/CIB Committee on Roofing Performance and ASTM D08 Committee on Roofing, Waterproofing and Bituminous Materials.

**RECENT RESULTS**

Martin, J. W., Embree, E. Stutzman, P. E., and Lechner, J. A., *Strength and Creep-Rupture Properties of Adhesive-Bonded EPDM Joints Stressed in Peel*, NIST Building Science Series 169, National Institute of Standards and Technology, May 1990.

Watanabe, H. and Rossiter, W. J., Jr., "Effects of Adhesive Thickness, Open Time, and Surface Cleanness on the Peel Strength of Adhesive-Bonded Seams of EPDM Rubber Roofing Membrane," in *Roofing Research and Standards Development: 2nd Volume, ASTM STP 1088*, T. J. Wallace and W. J. Rossiter, Jr., Eds., American Society for Testing and Materials, Philadelphia, PA, pp. 21–36, 1990.

Gaddy, G. D., Rossiter, W. J., Jr., and Eby, R. K., "Application of Thermal Analysis Techniques to the Characterization of EPDM Roofing Membrane Materials," in *Roofing Research and Standards Development: 2nd Volume*, *ASTM STP 1088*, T. J. Wallace and W. J. Rossiter, Jr., Eds., American Society for Testing and Materials, Philadelphia, PA, pp. 37–52, 1990.

Rossiter, W. J., Jr., Seiler, J. F., Jr., and Stutzman, P. E., "Characterization of Newly Fabricated Adhesive-Bonded Seams," *International Journal of Roofing Technology*, Volume 2, pp. 40–45, 1990.

Clifton, J. R., Rossiter, W. J., Jr., and Kaetzel, L. J. "Expert Systems for Roofing Construction," *International Journal of Roofing Technology*, Volume 2, pp. 57–60, 1990.

# QUALITY ASSURANCE LABORATORIES

## CEMENT AND CONCRETE REFERENCE LABORATORY

*Principal Investigator:* James H. Pielert
Building Materials Division
301.975.6704

*Sponsors:* American Society for Testing and Materials and
U.S. Army Corps of Engineers, Waterways Experiment Station

**OBJECTIVE:** To provide technical assistance, with ASTM Research Associates at BFRL, to public and private cement, concrete, aggregate, reinforcing steel, and pozzolan testing laboratories which use ASTM tests.

**PROBLEM:** Roads, bridges, water supply and sewage systems, buildings, airports, railroads, waterway systems, mass transit systems and other structures represent a substantial portion of the nation's wealth. Construction of these facilities is one of the nation's largest industries—about 10% of the Gross National Product. Over $4 billion of hydraulic cement is annually produced in the United States for use in $20 billion of concrete construction. Because of the large amounts of money and construction materials involved, standardization of testing to enhance the reliability of quality assurance measurements is of paramount concern. The productivity of the testing community in the cement and concrete fields can be increased by using correct procedures and apparatus which reduce testing errors and provide a sound basis for accepting cement on mill certificate. More efficient use of long-established construction materials are facilitated by dependable quality assurance programs.

**APPROACH** During 1991 BFRL will inspect 230 cement and/or concrete testing laboratories and issue inspection reports; distribute 2600 proficiency test samples and issue test reports; and prepare draft report on a CCRL research activity.

With the support of ASTM Research Associates working under BFRL supervision, services are provided to public and private cement and concrete testing laboratories on a voluntary basis. These services include on-site inspection of the laboratories and distribution of proficiency test samples. Equipment and procedures used in performing conventional quality assurance tests are evaluated for conformance to applicable national standards. Related test apparatus is checked with inspection equipment calibrated by NIST personnel.

Proficiency test samples of portland cement, pozzolan, concrete, blended cement and masonry cement are distributed at regular intervals to obtain information on laboratory performance. Additionally, technical studies are conducted in areas related to these programs. These are often in conjunction with other NIST units.

The primary benefit of the CCRL programs is improvement in the quality of testing in cement and concrete laboratories in the United States, Canada, and Mexico. Products include: 1) detailed report on each inspection performed; 2) comprehensive report on each round of proficiency sample testing; 3) input to the work of standards committees such as draft standards and data for use in the development or improvement of precision statements; and 4) reports on results of technical studies.

The managers of cement and concrete testing laboratories and the users of the services of such laboratories interact with BFRL through the CCRL reports. Summaries of proficiency sample data are provided to ASTM committees C1

and C9 for their use in developing or modifying standards. CCRL staff participate on ASTM standards committees. BFRL technical reports, papers in outside journals, and oral presentations are used as appropriate.

The CCRL programs benefits the materials testing laboratories and others involved with construction by: 1) improving the quality of laboratory testing; 2) providing data to quantify standard measurement techniques; and 3) providing direct communications between testing laboratories and standards-writing committees.

**RECENT RESULTS**

"Proficiency Testing as a Component of Quality Assurance on Construction Materials," Pielert, James, RILEM/ILAC Symposium, Paris, October 1990.

Inspected 220 cement and concrete testing laboratories and issued inspection reports.

Distributed 2600 proficiency test samples and issued reports of results.

## AASHTO MATERIALS REFERENCE LABORATORY

*Principal Investigator:* James H. Pielert
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301.975.6704

*Sponsor:* American Association of State Highway and Transportation Officials

**OBJECTIVE**

To provide technical assistance, with AASHTO Research Associates at BFRL, through on-site assessment of construction materials testing laboratories which use AASHTO test methods and distribution of proficiency test samples to public and private laboratories.

**PROBLEM**

The quality of testing in construction materials laboratories is an important concern when considering the overall question of quality construction. The importance of the testing function is demonstrated by The Strategic Highway Research Program (SHRP) which was initiated in 1987 as a five year, $150-million national highway and bridge pavement research program. Because of the large amounts of money and critical construction materials involved, standardization of testing to enhance the reliability of quality assurance measurements is important. The productivity of the testing community can be increased by using correct procedures and apparatus which reduce testing errors and provide a sound basis for the acceptance of materials on certificate. More efficient use of long-established construction materials and broader use of new materials are facilitated by dependable quality assurance programs.

**APPROACH**

During 1991 BFRL will 1) inspect 90 bituminous and 60 soil testing laboratories and issue inspection reports; 2) distribute 3900 proficiency test samples and issue test reports; and 3) prepare a laboratory inspection program for metals testing laboratories.

With the support of AASHTO Research Associates working under BFRL supervision, services are provided to public and private laboratories on a voluntary basis. These services include the on-site inspection of the laboratory and the distribution of proficiency test samples. The scope of the laboratory inspection

services includes testing of soils, bituminous materials, and plastic pipe, and measurements of frictional properties of highways. Equipment and procedures used in performing conventional quality assurance tests are evaluated for conformance to applicable national standards. Proficiency test samples of asphalt, soils, paint, aggregates and bituminous concrete are distributed at regular intervals to obtain information on laboratory performance.

Use of AMRL services is voluntary and provided only as requested by interested laboratories. FHWA through its Federal-Aid-Highway Manual requests that each state subscribing to AMRL services, authorizes copies of all inspection reports be forwarded to the appropriate regional and division offices. AMRL staff actively participate on standards committees and are often in leadership positions. Results of proficiency sample testing are routinely made available to ASTM and AASHTO committees. NIST technical reports, papers in outside journals, and oral presentations are used as appropriate.

The AMRL programs benefit construction materials testing laboratories and others involved with the nation's transportation systems in: 1) improving the quality of laboratory testing; 2) providing data to quantify standard measurement techniques; and 3) providing direct communications between testing laboratories and standards-writing committees.

The primary benefit of the AMRL programs is improvement in the quality of testing laboratories testing materials used in the transportation industry. Products include: 1) detailed report on each inspection performed; 2) comprehensive report on each round of proficiency sample testing; 3) input to the work of standards committees such as draft standards and data which can be used for precision statement development or improvement; and 4) reports on the results of technical studies.

**RECENT RESULTS**

Inspected 100 bituminous and 73 soils testing laboratories and issued inspection reports.

Distributed 3900 proficiency test samples and issued reports of results.

# REFRIGERATION MACHINERY

# PERFORMANCE OF CHLORINE-FREE ZEOTROPIC REFRIGERANT MIXTURES IN A HEAT PUMP

*Principal Investigator:* David A. Didion
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*Sponsors:* National Institute of Standards and Technology and
Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Global Emissions and Control Division

**OBJECTIVE** To determine the relative performance of binary zeotropic refrigerant mixtures which are comprised of fluorocarbons of the methane and ethane series.

**PROBLEM** Virtually all of the residential heat pumps and air conditioners in the U.S. operate with R22 as the working fluid. However, the ever growing concern about global warming endangers the future availability of this refrigerant because of its relatively high Global Warming Potential (GWP, 0.32 to 0.37). There is a paradox in trying to replace this fluid. R22 provides optimum balance between capacity and efficiency for this particular application. A single component refrigerant that could offer R22 performance is not known today and is not likely to be found in the future. Thus, attempting to replace R22 with another refrigerant of a lower GWP might well defeat the purpose. The new refrigerant would likely result in a lower equipment efficiency which would increase $CO_2$ generation at the power plant and thus increase global warming.

A possible solution is to use zeotropic mixtures where single refrigerant property deficiencies can be compensated for by mixing fluids of different properties and/or through improving heat exchanger performance by matching the temperature glide of the mixture. Whereas the challenge for mixtures prior to the threat of global warming was to exceed the performance of a heat pump using R22, their acceptance for tomorrow may depend only on having mixtures equal to R22 performance but with ozone-safe fluids.

**APPROACH** The research performed during FY 1991 will involve computer simulation and laboratory tests. Two newly-developed tools will be used: the computer model CYCLE-11 and the laboratory mini-breadboard. These tools enable the condenser and evaporator temperature profiles of both the refrigerant and counter flowing water to be quantified, and the heat exchanger areas to be optimized. In this way, relative performance of the respective working fluids can be fairly evaluated on an equal heat flux basis while avoiding pinch points and keeping pressure drop variations in vapor flow passages to a minimum.

Selection of mixtures will come from chlorine-free refrigerants: R14, R23, R32, R41, R116, R125, R134a, R143a, and R152a. All reasonable combinations of the refrigerants will be sorted out on the basis of physical properties such as boiling and critical points. The surviving binary candidates will be analyzed using CYCLE-11 over a complete range of composition for selected heat pump operating conditions in the heating and cooling mode.

The most promising mixtures will be evaluated in the mini-breadboard. Tests will be run nominally at each DOE steady state test rating point for both the heating and cooling modes. Water inlet temperatures will be the primary controlling

variable with each test. Capacity and COP will be the primary performance indicators; additional information on heat exchanger performance also will be determined which should enable heat exchangers to be sized for each mixture to achieve its maximum performance.

**RECENT RESULTS**

Didion, D. A., Cohen, R., and D. R. Tree, "The Role of R22 in Refrigerating and Air Conditioning Equipment," *Proceedings of the International Institute of Refrigeration Colloquium in Brussels*, March 1990.

Domanski, P. A. and M. O. McLinden, "A Simplified Cycle Simulation Model for the Performance Rating of Refrigerants and Refrigerant Mixtures," *Proceedings of the CFC/Purdue Conference*, July 1990.

## TERNARY ZEOTROPIC REFRIGERANT MIXTURES

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*Sponsor:* Department of Energy
Building Equipment Division

**OBJECTIVE**

To experimentally evaluate the thermodynamic and operational behavior of modified heat pump cycles and systems using ternary zeotropic refrigerant mixtures.

**PROBLEM**

Recent research interest in using zeotropic mixtures as working fluids for refrigeration systems has increased greatly. Substantial performance improvements using binary refrigerants have been demonstrated for air conditioning and heat pump operation. At the same time, limitations on the ability to obtain a desired two-phase temperature glide and temperature-enthalpy curve at a given capacity (or operating pressure) level have become apparent. These limitations have kept the observed performance improvements well under those theoretically predicted. This problem has been exacerbated by the reduction of available pure refrigerants for use in creating mixtures as a result of new environmental concerns. The additional degree of freedom provided by the third component in mixtures is expected to alleviate these problems by allowing use of a greater range of pure components and more precise tailoring of mixture properties to system requirements.

**APPROACH**

This research will be performed in two tasks. The first will evaluate experimentally and theoretically the thermodynamic and operational behavior of modified heat pump cycles using ternary mixtures. The NIST hard-sphere equation-of-state or the NIST SUPERTRAPP molecular simulation program will be used to select the most appropriate mixtures for examination. The NIST refrigeration cycle model will be modified to allow evaluation of intracycle heat exchange (thermal advanced cycles) appropriate to the application and the chosen mixture prior to experimental verification. Experimental verification will take place in BFRL's breadboard heat pump apparatus.

Tests will be performed with a binary mixture composed of the high and low boiler of the chosen ternary mixture and then with the ternary mixture to exemplify the benefit resulting from addition of the intermediate boiler. Evaporator heat source (water) glides will be set at values comparable to those used in

previous tasks on this apparatus. Because the ternary refrigerant mixtures will be more linear than previously studies binary refrigerant mixtures (e.g., R22/R114, R13/R12, R22/R11), it is anticipated that the ternary mixtures will show a higher efficiency than those previously observed, particularly through the control of temperature profile linearity via the third fluid.

In the second task, research will center on investigating the efficiency potential realized by internal heat exchange for refrigeration cycles with mixtures. An existing BFRL computer model will be modified to allow simulation of various forms of intracycle heat exchange for the operating conditions and refrigerant mixtures previously identified in the second subtask. Computer simulations will be verified by laboratory experiments.

**RECENT RESULTS**

Kauffeld, M., Mulroy, M., McLinden, M., and D. A. Didion, *An Experimental Evaluation of Two Nonazeotropic Refrigerant Mixtures in a Water-to-Water Breadboard Heat Pump*, NISTIR 90-4290, April 1990.

Didion, D. A. and D. Bivens, "The Role of Refrigerant Mixtures as Alternatives," *International Journal of Refrigeration*, Vol. 13, No. 3, pp. 163–175, May 1990.

Bushmeier, M., Mulroy, W., and D. A. Didion, *An Initial Laboratory Evaluation of a Single Solution Circuit Cycle for Use with Nonazeotropic Refrigerants*, NISTIR 90-4406, August 1990.

## MATSUSHITA HEAT PUMP EVALUATION—USING R22/R13B1

***Principal Investigator:*** David A. Didion
Building Environment Division
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***Sponsor:*** Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Global Emissions and Control Division

**OBJECTIVE**

To experimentally evaluate the thermodynamic and operational behavior of an innovative, commercially produced, residential heat pump equipped with a multiplate distillation apparatus for composition shifting of its zeotropic mixed refrigerant operating fluid.

**PROBLEM**

Two advantages resulting from the use of zeotropic refrigerant mixtures in heat pumps have been identified. The first is thermodynamic cycle improvement by matching refrigerant temperature glides to the heat source and sink. The second is load matching by composition shifting to a higher capacity refrigerant at low operating temperatures (which primarily saves energy by the reduction of the need for electric resistance heating). This project evaluates benefits from glide matching.

The heat pump to be examined, manufactured by the National division of the Matsushita Corporation, is commercially available on the Japanese home market but is not available on the U.S. market. The ductless indoor unit is comprised of the indoor coil, its blower, the thermostat and logic circuitry for a 0 to 10 volt analog signal to the inverter, and a wireless, remote controller for thermostat set point, blower and damper control. The outdoor unit model CU-223GR, includes

the outdoor coil, its fan, the inverter, the compressor and a multi-plate distillation column. This multi-plate distillation column is expected to provide the greatest amount of composition shifting practically possible and, hence, the greatest performance benefit likely from this control strategy with the chosen mixture, R22/R13B1.

**APPROACH**

During FY 1991, tests will be performed at the steady-state rating points of the DOE/NIST rating procedure for variable speed heat pumps. This test procedure is fully described in NISTIR 88-3781, *Recommended Procedure for Rating and Testing of Variable Speed Air Source Unitary Air Conditioners and Heat Pumps*. In addition to the data required by the DOE/NIST rating procedures, measurements will be made of compressor suction and discharge pressures, evaporator return bend temperatures, and mixture composition. This additional data will be used to evaluate the extent of composition shift attained and to help in evaluation of the zeotropic mixture effects on the cycle efficiency.

This project will provide the performance of the first commerical residential heat pump designed with refrigerant mixtures.

**RECENT RESULTS**

New project in FY 1991.

## IMPACT OF SURFACE ENHANCEMENT AND NEW OILS ON THE HEAT TRANSFER OF ALTERNATIVE REFRIGERANT

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301.975.5282

*Sponsors:* National Institute of Standards and Technology and
Electric Power Research Institute

**OBJECTIVE**

To develop the information necessary to design heat exchanger equipment using new alternative refrigerants-oil mixtures.

**PROBLEM**

The introduction of alternative refrigerants has solved the problem of ozone destruction in the stratosphere by chlorine and created another, lack of thermal design information for the new refrigerants. In a refrigeration machine, the refrigerant must be soluble with oil to ensure the lubricant returns to the compressor. Oils used with conventional refrigerants required chlorine in the refrigerant to affect solubility. Alternative refrigerants with little or no chlorine must operate with a new family of oils for which no heat transfer data exists.

Sanvordenker (1989) has experimentally shown that more energy will be required to operate a refrigerator with the alternative R134a than with the conventional refrigerant R12. This is typically what is being discovered with many of the alternative refrigerants and refrigeration applications. In order to combat increased system inefficiencies and the threat of enhanced global warming with the use of alternative refrigerants, the heat transfer capability of heat exchanger surfaces must be maximized to maximize system efficiency. This requires experimental and theoretical heat transfer studies of the particular working fluid with its oil.

**APPROACH**

BFRL will use two existing heat transfer/visualization rigs for this investigation. The first rig (enhanced rig) will be used to determine the impact of surface enhancements on the heat transfer of alternative refrigerants without oil. The second rig (oil rig) will be used to determine the impact of new oils on the heat transfer of alternative refrigerants in smooth tubes. In both cases, quantitative calorimetric data will be obtained in addition to completing the visualization studies.

Visualization of the flow is required to establish bubble sizes and frequencies which are fundamental parameters of vapor generation. The research will determine what fraction of the total heat flux is convected away and what fraction is used to generate bubbles. This will provide a better understanding and help optimize the fundamental parameters which govern nucleate boiling for the alternative refrigerants with and without the influence of oils.

The enhanced rig will be used to film at high speed the boiling process on current tube-side and shell-side surface enhancements. It will be possible to test many different boiling surfaces (e.g., external, plain, and enhanced).

The oil rig will be used to film at high speed the boiling process of alternative refrigerant-oil mixtures at various compositions within a smooth tube. Although less accurate calorimetric data is available on this rig, it should be sufficient to determine the influence of the polyalkyleneglycol (PAG) oils over their range of viscosity from ISO100 (automotive application) to ISO32 (refrigerator application) on the heat transfer effectiveness.

The research will be done in collaboration with leaders in the field of heat transfer, Professor Ralph L. Webb from Pennsylvania State University and Klaus Menze from Wieland-America Company. Professor Webb will complete complimentary experimental work in single tubes and a series of tube banks. His study will produce temperature, pressure, effective liquid velocity and heat flux data with various enhanced tubes with R11, R12, R22, R113, and the alternative refrigerants R123 and R134a. The visualization data obtained at NIST will be compared directly at the same heat flux, liquid velocity, temperature and pressure conditions and for the same surface enhancements. NIST's direct measurements of the components of the heat fluxes will then be used with Webb's data to develop improved correlations for the boiling of alternative refrigerants on commercially available enhanced surfaces.

Wieland-America will supply NIST with industrial guidance and enhanced boiling test sections. Wieland-America will also supply Professor Webb with enhanced tubes with the same enhanced surfaces to ensure direct comparison of results between Penn State and NIST. Wieland-America will conduct full evaporator tests during this same period so that another comparison of data will be possible.

**RECENT RESULTS**

Kedzierski, M. A. and D. A. Didion, "Visualization of Nucleate Flow Boiling for a R22/R114 Mixture and Their Components," *Experimental Heat Transfer*, Vol. 3, pp. 447–463, 1990.

Kedzierski, M. A. and D. A. Didion, "A Comparison of Experimental Measurements of Local Flow Boiling Heat Transfer Coefficients for R11 and R123," *Proceedings of the Third ASME-JSME Thermal Engineering Joint Conference*, held in Reno Nevada, March 1991.

# BUILDING CONTROLS

# COMMUNICATION PROTOCOLS FOR BUILDING CONTROLS

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*Sponsors:* National Institute of Standards and Technology and
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Federal Energy Management Program

**OBJECTIVE** To assist the building industry develop, evaluate, and test Communication Protocol Standards for the open exchange of information between equipment from different control vendors and between different levels of control in both hierarchal and distributed building management systems (BMS).

**PROBLEM** Since 1975, automatic control systems in buildings have changed from pneumatic control systems to supervisory Energy Management and Control Systems (EMCS) to distributed direct digital control (DDC) systems. Recently, the development of local area networks has made it possible to distribute "intelligence" through-out a building with more of it being placed at both the highest and lowest levels. In the future, integrated building services, combining EMCS, fire detection, security, data processing and communications, are likely to be increasingly in demand due to their potential to reduce first costs, simplify maintenance, and make operator training easier and quicker.

**APPROACH** BFRL is conducting a multi-year research effort to:

1. Assist ASHRAE, IBI, and the building industry develop standard communication protocols for the exchange of building service information between different vendor systems and between different levels of intra-system communication.

2. Provide testing and evaluation facilities to study different protocols and to determine compliance of vendors' equipment to proposed or finalized standards.

3. Develop and verify a "reference implementation" of proposed and final protocol standard and develop procedures for performance and compliance testing.

4. Develop a performance testing suite to facilitate protocol evaluation at each level of system communication and serve as diagnostic tools for trouble shooting and assigning responsibility in the case of integrated systems provided by multiple vendors.

5. Develop guide specifications, test methods, and diagnostic procedures to evaluate the performance of complex integrated hardware-software systems.

6. Conduct research which will lead to a new generation of tools to design and evaluate building communication systems encompassing integrated services. This research will be performed with private industry.

This research concentrate on assisting ASHRAE's SPC 135 committee develop a new EMCS Communication protocol draft standard suitable for public review;

developing a revised BFRL abstract Test Suite, and creating a "Test Implementation" based upon the BFRL Abstract Test Suite.

**RECENT RESULTS**

Bushby, S. T. and H. Michael Newman, "BAC-net-The Emerging Communication Protocol for Building Automation Systems," *ASHRAE Journal*, April 1991.

Bushby, S. T., "Testing Conformance to Energy Management and Control System Communication Protocols—Part 1: Test Architecture," *ASHRAE Transactions*, Vol. 96, Part 1, January 1990.

Bushby, S. T., "Testing Conformance to Energy Management and Control System Communication Protocols—Part 2: Test Suite Generation," *ASHRAE Transactions*, Vol. 96, Part 1, January 1990.

## EMULATION AND DIAGNOSTIC METHODS FOR EVALUATING BEMS PERFORMANCE

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*Sponsors:* National Institute of Standards and Technology and
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Building Systems and Materials Division

**OBJECTIVE**

To develop methods to evaluate the performance of and diagnose problems with Building Energy Management Systems (BEMS) using building/HVAC emulators.

**PROBLEM**

The proper operation and control of buildings involves complex interactions of numerous control loops and many pieces of equipment. To successfully operate and control buildings the development of a new generation of computerized Building Energy Management Systems (BEMS) and, in particular, test methods and diagnostic tools for evaluating their performance must be performed. Research is needed on: 1) to develop test procedures and instrumentation evaluate the performance of current and future BEMS, and 2) to create a new generation of "tools" to provide diagnostic information on BEMS application software. These tools could be incorporated into the BEMS systems by manufacturers to assist in making real-time control decisions.

**APPROACH**

During FY 1991, BFRL perform the following research in conjunction with the International Energy Agency (IEA) Annex 17 Committee on BEMS Performance. It consists of three tasks:

1. Perform a planned Annex 17 exercise, using the BFRL Emulator/Tester developed last year to test several BEMS by different Annex 17 participants.

2. Develop draft test procedures and performance criteria, while working with other Annex 17 members, to evaluate BEMS performance which could serve as the basis for future international standards.

3. Use the BFRL Emulator/Tester in a DoE funded BEMS Test Bed Environment so U.S. control companies could try out and validate different

approaches to building diagnostics and universities and BFRL could conduct advanced research on new diagnostic and building optimization methods.

**RECENT RESULTS**

Kelly, G. E. and W. B. May, "The Concept of an Emulator/Tester for Building Energy Management System Performance Evaluation," *ASHRAE Transactions*, Vol. 96, Part 1, 1990.

Kelly, G. E., Park, C., and J. P. Barnett, "Using Emulator/Testers for Commissioning EMCS Software, Operator Training, Algorithm Development, and Tuning Local Control Loops," *ASHRAE Transactions*, Vol. 97, Part 1, 1991.

## DESIGN GUIDELINE FOR VAV SYSTEMS

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*Sponsor:* General Services Administration
Public Buildings Service
Office of Real Property Development

**OBJECTIVE**

To develop a Design Guideline for Variable Air Volume (VAV) Systems in GSA owned and operated buildings.

**PROBLEM**

VAV Systems are recognized as effective energy saving air handling systems that can be installed in modern office buildings. However, numerous problems associated with their design and operation have been documented. These problems include poor air quality, inadequate supply of ventilation air, control instability, system noise, inability to meet loads under certain conditions, poor humidity control, insufficient ventilation air, and pressurization imbalances making it difficult to open doors. The sources of most of these problems are well understood and can often be traced to inadequate design. This research will involve surveying VAV in existing GSA buildings, determining what works and what does not, and relating problems to design inadequacies.

**APPROACH**

During FY 1989 BFRL performed a survey of six GSA buildings to determine the general characteristics of installed VAV systems and to identify problems with different designs and operating practices. The survey included Vdiscussing AV operating and performance issues with building managers, operating staff, and occupants, and analyzing data on zone air flow rates, zone temperatures and ventilation air quantities, where available. In FY 1990, this survey was expanded to cover 12 buildings. This gave a more complete understanding of how different VAV designs affect system performance. Also during FY 1990, three buildings were selected for in-depth inspection and testing. The knowledge gained from these surveys and tests, along with information obtained from a review of published research results on the performance of VAV systems, and recommendations provided by technical experts in the field (particularly those associated with control companies) will then be used to develop a Design Guideline for VAV Systems.

The Design Guide for VAV Systems will be completed and used to assist GSA in getting better performing VAV Systems in their buildings. The guideline will address the subjects of configuration, zoning, equipment, controls, types of components, sizing, noise, ventilation, distribution.

**RECENT RESULTS** Kao, J. *Variable Air Volume System Design Guide*, NISTIR June 1991.

## ASSESSMENT OF GSA'S PERFORMANCE GUIDE SPECIFICATIONS DESIGN/BUILD OFFICE BUILDINGS

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Office of Real Property Development

**OBJECTIVE** To review GSA's "Performance Guide Specifications Design/Build Office Buildings" document for criteria enhancement, addressing both performance requirements and verification procedures.

**PROBLEM** The GSA document "Performance Guide Specification Design/Build Office Buildings" was completed in June 1990. These specifications define the general policy and detailed requirements for the design and construction of GSA managed buildings through the design/build delivery approach. It is intended to reflect basic functional, safety, and environmental needs of federal agencies.

**PROBLEM** A general review of the contents of the Guide Specifications will be conducted and any deficiencies that are found will be identified. Special attention will be given to sections involving architectural exterior envelop design, equipment rooms, environment consideration relating to interior design (such as lighting and acoustics), mechanical system design criteria, cooling and heating systems, air distribution, fire protection, temperature control systems, and building structural systems. Comments will support the objective of being contractually specific, technically correct, and procedurally feasible and appropriate. The knowledge and experience of qualified experts in various fields will be obtained, as needed.

BFRL will evaluate the sensitivity and importance of various design criteria and determine the adequacy of their coverage in the specifications. BFRL also will determine if the commissioning and conformance testing requirements covered in the document should be strengthened and/or supplemented.

The final report will include detailed recommendations on how to improve the content of these specifications. Comments will reflect possible modifications to testing and/or content requirements, so as to clearly direct future required revisions. This review will assist GSA evaluate their recently-developed Performance Guide Specification Manual for Design/Build Office Buildings and to recommend improvements.

**RECENT RESULTS** New project in 1991

# INDOOR AIR QUALITY

# INDOOR AIR QUALITY MODELING

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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To construct a laboratory facility for the validation of contaminant dispersal models and interzonal airflow models.

**PROBLEM** BFRL has developed advanced indoor air quality analysis programs to predict the concentrations of contaminants in multi-zone building airflow systems. These programs account for the varied physical mechanisms involved in contaminant dispersal including interzone airflow, filtering, adsorption, desorption, and chemical reactivity. There are little data in the literature that can be used to validate these models and much of the data that exists lack measurement on many parameters required to model the experiments. Existing data are often obtained in experiments characterized by insufficient control of many of the crucial parameters, such as measurements made in uncontrolled "test houses." There is a need to acquire data to validate multi-zone indoor air quality models, and the use of a controlled, laboratory facility would be particularly appropriate to such validation efforts.

**APPROACH** A reconfigurable multi-zone test facility was designed during FY 1990 for construction in one of the environmental chambers in Building 226. This facility was designed to investigate the ability of state-of-the-art contaminant dispersal models to predict contaminant concentrations in multi-zone building airflow systems as they are determined by interzone airflow, filtering, reactivity, adsorption and desorption. This project will consist of three efforts directed towards constructing the multi-zone validation facility and the experimental program of validation using the facility.

1. Contaminant dispersal modeling using CONTAM87 will be conducted on the proposed facility to finalize the design of the facility's instrumentation and data acquisition systems and for planning the experimental program.

2. A single zone test chamber will be designed and constructed, and preliminary experiments will be conducted in this same chamber. The validation facility design calls for one of the chambers of the facility to be constructed differently from, and instrumented in greater detail than, the other chambers. This chamber is intended for use in single zone tests to determine model parameters, such as adsorption coefficients and reactivity constants, for use in subsequent multi-zone validation experiments. Experiments will be conducted to determine parameters such as adsorption coefficients and emission rates for building materials.

3. Final design and initial construction of the multi-zone validation facility will use the design developed in FY 1990. This facility will be instrumented for the measurement and control of interzone airflows and temperature and the measurement of contaminant concentrations. The facility's instrumentation system will also incorporate a multi-zone tracer gas measurement system.

**RECENT RESULTS** Axley, J. W., *Adsorption Modeling for Macroscopic Contaminant Dispersal Analysis*, NIST GCR 90 573, February 1990.

## THREE-DIMENSIONAL MODELING OF AIR AND CONTAMINANT MOVEMENT IN INTERIOR SPACES

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*Sponsors:* National Institute of Standards and Technology and
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Building Systems and Materials Division

**OBJECTIVE** To apply three-dimensional computer models for predicting room air motion to mechanically ventilated office spaces in order to study air movement patterns, ventilation effectiveness, thermal comfort, and contaminant distributions.

**PROBLEM** The concentrations of indoor pollutants within a space are a complex function of pollutant source characteristics, ventilation rates and ventilation air distribution, and the various physical mechanisms of contaminant dispersal such as absorption and chemical reaction. The level of thermal comfort within a space also depends on ventilation rates and air distribution along with the distribution and intensity of heat loads and other thermal characteristics of the space. The maintenance of acceptable indoor air quality within buildings, including the control of pollutant levels and the provision of adequate thermal comfort, at a reasonable energy cost requires a detailed understanding of flow fields and concentration distributions within ventilated spaces and the factors that affect these distributions. More information is needed on how room air motion is affected by ventilation system configurations, airflow rates and temperatures, and the arrangement of interior furnishings.

**APPROACH** Finite difference computer models have been developed for predicting three-dimensional airflow fields and contaminant concentration distributions in ventilated spaces. These models have been formulated based on fundamental mass, momentum and energy balance equations coupled with expressions for the transport of turbulent kinetic energy and its dissipation. The performance of these micro-models have been evaluated by comparing the predicted results of buoyant enclosure flows with published experimental data, and the agreement between the predictions and measurements has been reasonably good. BFRL developed the ability to apply one such model EXACT3 to mechanically ventilated spaces in modern office buildings to study ventilation effectiveness and thermal comfort performance in these buildings. During FY 1990, BFRL used EXACT3 to study the issues of ventilation effectiveness and thermal comfort prediction for modern, mechanically ventilated office spaces.

During FY 1991 BFRL will extend this effort to study the effects of ventilation system parameters and interior configurations on interior room air motion for realistic representations of modern office space. For various combinations of these parameters describing the ventilation system performance and the office space use, the model will be used to predict general patterns of room air motion,

the Air Diffusion Performance Index (ADPI), ventilation effectiveness and contaminant distribution patterns. This information will in part serve to evaluate the usefulness of the various measures of ventilation effectiveness that have been proposed. These results will be useful to the expected revision to ASHRAE Standard 62-1989 and the development of ASHRAE SPC129P, and provide information useful to revising the ASHRAE Handbook of Fundamentals on the design of office space and ventilation systems from the perspective of air distribution.

**RECENT RESULTS**

Kurabuchi, T., Fang, J. B., and R. A. Grot, *A Numerical Method for Calculating Indoor Airflows Using a Turbulence Model*, NISTIR 89-4211, January 1990.

Fang, J. B. and R. A. Grot, "Numerical Simulation of the Performance of Building Ventilation Systems," *ASHRAE Transactions*, Vol.96, Pt.1, January 1990.

## ENVIRONMENTAL EVALUATION OF NEW FEDERAL OFFICE BUILDINGS

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*Sponsor:* General Services Administration
Public Buildings Service
Office of Real Property Development

**OBJECTIVE**

To evaluate thermal envelope performance and indoor air quality characteristics of new federal office buildings.

**PROBLEM**

The design and construction of modern, office buildings places stringent requirements on the building's thermal and environmental performance. A better understanding of the thermal, environmental and operational characteristics of these buildings is essential to avoid design, construction and operational errors that may result in a building unsuited to its tenants. Such information is especially important during the pre-occupancy and early occupancy stages, when many adjustments and modifications are being made to provide an acceptable level of performance. Previous studies have shown the value of diagnostic evaluations in assessing building performance, and have revealed the importance of building envelope air leakage in determining space conditioning loads and the performance of building ventilation systems. The use of a building Diagnostic Center with continuous computer based monitoring capability has been particularly revealing when coordinated with envelope thermography and tracer gas decay measurements of air exchange rates. These test methods can also reveal the migration of contaminants from one part of a building to another (for example, underground and attached garages and printing and photographic processing area into the occupied parts of the building) and problems associated with nonuniform distribution of ventilation air, poor ventilation effectiveness. Many processes and activities that are not anticipated in the design can also cause indoor air quality and comfort problems.

**APPROACH**

In past years, BFRL developed design specifications for the installation of diagnostic centers in new office buildings, and performance criteria and programming directives related to the installation of such diagnostic centers. The diagnostic center concept is intended to be applied to three federal buildings in Portland,

OR, Overland, MO and Long Beach, CA. The diagnostic centers in these buildings are designed to facilitate the evaluation the performance of the building ventilation systems, the natural and induced building air leakage, the adequacy of the interior environment and the level of airborne contaminants.

In 1988-89 a diagnostic center was used in the Portland East Federal Building for pre-occupancy and early occupancy testing. The diagnostic center installation in the Overland Building was completed during FY 1990 and preoccupancy tests were conducted. With building occupancy scheduled to begin in December 1990, early occupancy testing will begin. Another diagnostic center installation was planned during FY 1990 for the Long Beach Federal Building, but was not completed due to building construction delays.

During FY 1991 BFRL will conduct the early occupancy testing of the Overland Building and install the Long Beach diagnostic center when the construction schedule permits. This testing will include long-term measurements of indoor pollutant levels and building air exchange rates. The contaminants to be monitored will include carbon dioxide, carbon monoxide, radon, formaldehyde, respirable particles and volatile organic compounds. Preoccupancy testing will be conducted in the Long Beach building both during and after the diagnostic center installation. A thermographic inspection will also be conducted in the Long Beach Building to evaluate the thermal integrity of the building envelope.

The results of this project will enable GSA to determine the performance of three high technology office buildings and to establish guidelines for the design and operation of future buildings.

**RECENT RESULTS**

Persily, A. and Doles, W. S., "Pressurization Testing, Relation of CO2 Concentration to Office Building Ventilation, ASTM, STP1067, 1990

Grot, R. A. and Persily, A., *Environmental Evaluation of the Portland East Federal Office Building Preoccupancy and Early Occupancy Results*, NISTIR 89-4066, NIST, 1989.

Persily, A., "Ventilation Rates on Office Buildings," *The Human Equation—Health and Comfort*, ASHRAE IAQ89, 1989.

## VENTILATION EFFECTIVENESS IN MODERN OFFICE BUILDINGS

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*Sponsor:* Department of Energy
Building Systems and Materials Division

**OBJECTIVE**

To develop and demonstrate test methods for evaluating the uniformity of air distribution within modern, mechanically ventilated office buildings.

**PROBLEM**

The control of pollutant source strengths and the provision of adequate air exchange rates are the two basic factors that determine pollutant levels inside buildings and the corresponding potential for indoor air quality problems. Even when the net air exchange rate of a building is adequate to prevent air quality problems, if this ventilation air is not well distributed throughout the building then there may be areas with inadequate supply of outdoor air and the potential for indoor air quality problems. Also, if air distribution is not good then higher ventilation airflow rates are required to maintain acceptable air quality, and excessive amounts of energy will be consumed by that additional ventilation. The existence of nonuniform air distribution or poor ventilation effectiveness has been suspected by some to be responsible for many indoor air quality problems. However, the difficulty of measuring ventilation effectiveness in the field has prevented the determination of whether, to what extent and under what conditions nonuniform air distribution is a problem in buildings. ASHRAE SPC129P has been trying to develop a standard test method for measuring ventilation effectiveness in office buildings for several years, but has been unable to make significant progress due primarily to the lack of demonstrated measurement techniques. ASHRAE Standard 62-1989, the ventilation standard, makes reference to the impact of ventilation effectiveness, but without the means to predict or measure ventilation effectiveness the designer can not effectively account for nonuniformities in air distribution.

**APPROACH**

Test methods have been developed and applied by BFRL to measure many aspects of air exchange in mechanically ventilated office buildings, and the results of these measurements have been used to further the understanding of the relationship between office building air exchange and indoor air quality. These test methods include tracer gas procedures for measuring ventilation rates and interzone airflow rates. More recent work by BFRL for DOE was concerned with the development of tracer gas measurement techniques for quantifying ventilation effectiveness in the field. Progress has been made on several promising approaches for making these measurements, but additional work is needed before a reliable test method is available. BFRL will build on their work to further develop these ventilation effectiveness techniques with the goal of a reliable and straightforward test method for measuring ventilation effectiveness in the field. Measurements will be made in two new office buildings with both open office space and individual offices to develop experience with the measurements, provide an indication of the repeatability of the measurements, and begin developing a database of ventilation effectiveness measurements in the field.

This effort is expected to contribute to the efforts of ASHRAE SPC 129P in their work to produce a standard test method for measuring ventilation effectiveness, and the anticipated revision of ASHRAE ventilation standard 62-1989.

**RECENT RESULTS**

Persily, A. K. and W. S. Dols, "Field Measurements of Ventilation and Ventilation Effectiveness in an Office Library Building," Proceedings of the 11th *AIVC Meeting*, September 1990.

Persily, A. K. and J. W. Axley, Measuring Airflow Rates with Pulse Tracer Techniques," *Air Change Rate and Airtightness in Buildings,* ASTM STP 1067, pp. 31–51, February 1990.

Persily, A. K. and W. S. Dols, "The Relation of CO2 Concentration to Office Building Ventilation," *Air Change Rate and Airtightness in Buildings,* ASTM STP 1067, pp. 77–92, February 1990.

Persily, A. K. and W. S. Dols, *Ventilation and Air Quality Investigation of the Madison Building Phase I Report*, NISTIR 89-4219, December 1989.

## COMPARISON OF VENTILATION MEASUREMENT TECHNIQUES

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*Sponsor:* Bonneville Power Administration

**OBJECTIVE** To compare different methods of measuring outdoor air ventilation rates and assess the accuracy of these methods, and to make ventilation rate measurements in a mechanically ventilated office building for comparison to previous measurements in that same building.

**PROBLEM** Ventilation standards that specify minimum levels of ventilation for occupant health and comfort have existed for many years. These have traditionally been design standards, requiring that the building design specifications comply with the provisions of the standard. It has become increasingly apparent that design values for ventilation rates are not always realized in practice both when the building is constructed and later on after the building has been in operation for some time. The realization that design objectives and the requirements of ventilation standards are not always achieved in practice, along with increased concerns about indoor air quality, has led to the need for on-site verification that building ventilation rates are in compliance with design values and/or ventilation standards. The requirement for on-site verification, or commissioning, has led to a need for cost-effective and accurate procedures for making field measurements of building ventilation rates. In addition, questions exist regarding how much building ventilation rates change over time and how often such field assessments need to be conducted.

**APPROACH** This project will involve two aspects of ventilation rate measurement in mechanically ventilated commercial buildings, a comparison of measurement methods and the reassessment of ventilation rates in an office building. The comparison of measurement methods will involve the application of several techniques for assessing ventilation in the Portland East Federal Building. These techniques will include tracer gas decay measurements of whole building air exchange rates, estimations of air exchange rates based on peak values of indoor carbon dioxide concentrations, direct measurements of airflow rates in the ventilation system ductwork using traditional airflow rate measurement devices (e.g., pitot tube and hot-wire anemometer traverses), and measurements of the percent of outdoor air intake using tracer gas, occupant generated carbon dioxide and temperature balances between the return, intake and supply airflows. These various measurement techniques will be applied in the Portland East Building and the results will be analyzed for consistency and accuracy.

In the second part of the project, a series of air exchange rate measurements will be conducted in the Portland East Building using an automated tracer gas decay system. Air exchange rates were measured in this building several years ago by BFRL as part of a project sponsored by the Public Buildings Service of the General Services Administration. New measurements of air exchange rates will be

conducted in the building during each season of the year to determine whether and by how much the air exchange rates have changed from ventilation system operation strategies, ventilation control system sensor calibration drift, and other factors.

The results of this project will be accurate procedures for making field measurements of building ventilation rates for verification that rates are in compliance with design standards.

**RECENT RESULTS** New project in 1991.

## ENVELOPE DESIGN GUIDELINES

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*Sponsor:* General Services Administration
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Office of Real Property Development

**OBJECTIVE** To develop an envelope design guide for federal office buildings.

**PROBLEM** In an effort to reduce energy use and to ensure a comfortable and healthy indoor environment, a massive amount of field, laboratory, and analytical research was performed in the U.S. during the past decade on understanding, controlling and modeling thermal performance of building envelopes, infiltration and air leakage in buildings, improvement of building ventilation systems, and control of moisture damage in buildings. This research has increased the knowledge of building envelope performance, building air tightness, principles governing air infiltration, migration of moisture into and through building envelopes, and interaction of building envelope tightness and performance of ventilation systems. It has also revealed that the design of a cost-effective building envelope system which has good thermal performance, is air tight, resists moisture penetration and damage, and permits effective introduction of outdoor air into a building is not a simple process when all performance requirements are considered.

At present there are no guidelines for the design and construction of commercial building envelopes which include the results of this research.

**APPROACH** BFRL will develop a guide for the proper design and construction of federal building thermal envelopes. The envelope design guide will be based on the principles involved in the design of a thermally efficient building envelope that is resistant to air-infiltration and moisture transfer. It also will address the importance of the envelope design on the performance of the building ventilation system.

The emphasis of this guideline will be on the practical application of these principles to building design and construction. The information will be presented in a straightforward manner including case studies of "do's and don'ts" with graphic representations. The case studies will be aimed at a target audience of architects and engineers in order to have maximum impact on future building practice.

The development of this guideline builds on a past effort that included the development of a format for the guideline, the technical review of recent research on thermal and air tightness performance of commercial building envelopes, and the identification of technical contributors that could serve as a resource to NIST in developing the guideline. BFRL contracted with the National Institute of Building Sciences to solicit voluntary contributions to the guidelines, to maintain liaison with organizations interested in the guideline development, and to coordinate a technical review of the guidelines when they are completed.

During FY 1991 NIST will prepare the envelope design guideline based on in-house expertise, the material obtained from outside technical experts and the material obtained by NIBS from voluntary contributors. The design guide will present recommended design and construction practices for thermal, air leakage, ventilation, and moisture transfer performance.

**RECENT RESULTS**

Persily, A. K., *Development of Thermal Envelope Design Guideline for Federal Office Buildings*, NISTIR 90-4416, October 1990.

# COMPUTER INTEGRATED CONSTRUCTION

# INFORMATION EXCHANGE TECHNOLOGIES IN THE BUILDING PROCESS

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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop and implement the technical basis for correct and efficient information interchange standards for the building industry.

**PROBLEM** The use of computers has penetrated every aspect of the building process, including design, construction, and operation. Integration of these traditionally separate activities is proceeding slowly because there exist few effective standards for expressing and exchanging information about buildings.

Participants in the building process continue to be plagued by the errors and inefficiencies that occur because information is not available in digital form when needed, is incorrectly transferred out of a sending system, or is incorrectly interpreted by the receiving system. In addition, the information must be broken up into multiple incompatible forms because the available standards for digital information interchange have limited scopes. Rational techniques are needed for developing and testing information interchange standards if computer integration of the building process is to be achieved.

The existing national standard for product data exchange, the Initial Graphics Exchange Specification (IGES), deals mostly with basic data describing non-geometric and geometric elements and their graphical representation. The specification lacks the appropriate protocols required to ensure its successful use in specific applications, as well as the supporting methodology and test cases required to validate specific software implementations. Continued work to make IGES useful in the building industry is essential, since alternatives will not be available commercially for years.

Based on the IGES experience, national and international groups of technical experts are engaged in developing the next generation standard, called the Standard for Product Model Data Exchange (STEP), within the framework of ISO TC184. The US national effort is called Product Data Exchange using STEP (PDES).

Unlike IGES, the new standard is intended to facilitate the exchange of complete product model data sets. Typical building industry product data impose harder requirements on STEP than do those of the mechanical products industry, because of the larger mix of disciplines and activities that must be served, and because of the greater complexity of the typical product—a building with multiple interacting systems as compared to a mechanical assembly. The building industry needs to influence the development of STEP in its early stages to ensure that its core capabilities are sufficiently complete and sufficiently integrated for the building industry's purposes.

**APPROACH**

BFRL will continue to develop the application protocol methodology and the required testing methodologies for ensuring reliable data exchange. For IGES, this will include refining the first prototype, the "3D Piping IGES Application Protocol," developed in FY 1989/1990. For STEP, BFRL will develop the "Guidelines for the Development and Approval of STEP Application Protocols" and will generalize to STEP the testing methodologies developed for IGES.

BFRL will continue working to develop an adequate integration framework for STEP. The preliminary STEP Framework that was developed by BFRL in FY 1990 are being worked out in considerable detail. Existing models are being integrated into a a collection of resource modules that are responsive to information requirements of multiple industries and disciplines. A methodology for interpreting the integrated resource in specific applications is also under development.

The BFRL work will be presented to and coordinated with the national and international standardization committees through continued participation in the US IGES/PDES Organization and the working groups of ISO TC184/SC4. CBT will continue to support the US Technical Advisory Group for TC184/SC4.

**RECENT RESULTS**

Danner, W. F., Sanford, D. and Y. Yang, *STEP (Standard for the Exchange of Product Model Data) Resource Integration—Semantic & Syntatic Rules*, NISTIR 91-4528, March 1991.

Danner, W. F. and P. Leppanen, "A Case Study of the Conceptual Product Modelling of Buildings: Prefabricated Reinforced Concrete Structure," *Proceedings of CIB Conference*, October 1990.

Palmer, M. E. and Reed, K. A., *3D Piping IGES Application Protocol Version 1.0*, NISTIR 90-4420, September 1990.

Danner, W. F., *A Proposed Integration Framework for STEP (Standard for the Exchange of Product Model Data)*, NISTIR 90-4295, April 1990.

Pearson, M. R., Palmer, M. E., Crusey, J. L., Bracken, C. L., Mankins, L. A. and D. O. Remington, *Overview of the IGES/PDES Testing Project*, NISTIR 89-4207, December 1989.

## PRODUCT DATA EXCHANGE STANDARDS IN SHIPBUILDING

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*Sponsor:* Department of Navy
Navy Sea Systems Command

**OBJECTIVE**

To develop the technical basis for correct and efficient information interchange standards for the shipbuilding industry.

**PROBLEM**

The Navy/Industry Digital Data Exchange Standards Committee (NIDDESC) was formed in 1986 as a joint project of the U.S. Navy Sea Systems Command and the National Shipbuilding Program of the Society of Naval Architect and Marine

Engineers. NIDDESC is a cost-sharing, cooperative effort involving Navy and industry experts in CAD Applications.

NIDDESC identified work needed to reach its objective: identify and agree on the data to be transferred; agree on the neutral data formats to be used; develop and acquire translators; test and validate translators with approved procedures.

In previous work, NIDDESC participants focused on developing consensus on the product data to be transferred and on driving the development of the Initial Graphics Exchange Specification (IGES: ANSI Y14.26M), of the MIL-D-28000 Digital Representation for Communication of Product Data, and of the Standard for the Exchange of Product Model Data (STEP: ISO 10303). NIDDESC identified and agreed on data to be transferred for builders level descriptions of ships structure, piping, HVAC and electrical distribution systems. NIDDESC was the principal contributor to the 3D Piping IGES Application Protocol that has been submitted for inclusion in MIL-D-28000. Working through the U.S. activity called Product Data Exchange using STEP (PDES), NIDDESC was successful in incorporating its data requirements for ship structures in the December 1988 Committee Draft of STEP. As of 1990, however, consensus had not been reached on STEP.

In May 1990, the NIDDESC Steering Committee directed the Working Group to accelerate the implementation of digital data transfers in the marine industry. The result of this acceleration effort is expected to be an invocable data transfer specification defining explicit data exchange format and including Navy/Marine Industry approved test cases and validation procedures. To the maximum extent possible, this specification is to be consistent with ongoing STEP developments and will be structured as a set of extended-STEP application protocols. NIDDESC will continue to work toward incorporation of its results into the national and international standardization process.

In addition to developing product data exchange capabilities for the next generation CAD systems, NIDDESC will investigate the requirements necessary to ensure the successful digital exchange of engineering drawings in order to support existing CAD system work. The result of this effort is expected to be an IGES Application Protocol.

**APPROACH**

BFRL has led the development of the application protocol methodology in the both U.S. IGES/PDES Organization and the ISO TC184/SC4 STEP activity.

During FY 1991, BFRL will use this methodology, to develop guidelines for testing and validating NIDDESC/STEP application protocols and provide technical support for the development of an Engineering Drawing IGES Application Protocol.

BFRL will review NIDDESC information models for ship structure and piping, HVAC, and electrical distribution systems and will provide feedback and proposed modifications to the model owners.

BFRL will provide technical support for testing and validating NIDDESC information models, including database management system support and assistance in creating database queries. BFRL will provide feedback and proposed changes to the model owners.

BFRL has led the development of the STEP integration framework and methodology. BFRL will provide technical support for the creation of application interpreted models (AIMs) from the NIDDESC application reference models (ARMs) using this methodology. BFRL will provide feedback and proposed modifications to the model owners.

This project will provide the technical basis for the development of IGES/PDES/STEP information exchange standards so they adequately address the needs of the shipbuilding industry.

**RECENT RESULTS**

New project in 1991.

# HEAT AND MOISTURE TRANSFER

# MEASUREMENT OF CAPILLARY TRANSPORT PROPERTIES FOR MATERIALS

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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop capillary transport properties for common building materials.

**PROBLEM** Reliable moisture property data, needed as input for the NIST Moisture Transfer Model and other moisture transfer models reported in the literature, are unavailable. An examination of the moisture property data for common building materials reveals 1) diffusion coefficients measured by different laboratories vary markedly, 2) capillary diffusivity data exist for only a few common building materials, and 3) sorption isotherms (i.e., moisture content versus relative humidity) and suction curves (i.e., capillary pressure versus moisture content) do not exist for many important building materials.

The NIST previously developed a distributed-capacity, finite-difference model that predicts the combined transfer of heat and moisture in multi-layer construction under non-steady-state conditions. The model includes vapor diffusion, capillary, and convection transfers (i.e., transfer by air infiltration and exfiltration), and includes the important couplings between heat and moisture transfer. This model is capable of simulating the moisture performance of a wide range of constructions, and it uses weather data from Weather Years for Energy Calculations (WYEC).

This NIST Moisture Transfer Model was used in FY 1990 to conduct a ensitivity analysis of the moisture accumulation in a wood-frame wall subjected to winter climate. In this study, significant parameters affecting moisture build-up in wall construction were identified, and moisture management strategies were recommended.

During FY 1990, vapor diffusivities and sorption isotherms for ten common building materials were measured. These measurements considerably extended the accuracy and usefulness of the NIST Moisture Transfer Model. A state-of-the-art centrifuge was purchased and checked out as suitable for capillary pressure measurements.

**APPROACH** During FY 1991, BFRL will perform capillary property measurements for the following building materials: wood, wood-fiber board, asphalt impregnated sheathing, plywood, cellulose insulation, and concrete. For each of the materials, the following measurements will be carried out:

*Capillary Pressure Curves*. Cylindrical specimens for each of the materials will be spun in a centrifuge with the bottom surface exposed to liquid water. Capillary pressure will cause water to be drawn into the cylindrical specimen. At each position, the body forces on the water caused by the centrifugal motion will balance the capillary pressure forces. In this situation, a gradient in capillary pressure and moisture content will develop along the longitudinal axis of the cylindrical specimen. A plot of the resulting capillary pressure versus moisture

content is called a "capillary pressure curve" and is an unique material property. Separate capillary pressure curves will be measured for test specimens initially dry and initially saturated with water.

An attempt will be made to reduce the above capillary pressure measurements to a single correlation using the Leverett j-function. Such a correlation will permit the capillary pressure for other building materials to be estimated based upon much more simple measurements of liquid permeability and porosity.

*Liquid Permeability Measurements*. The flow rate through a porous disk-shaped specimen saturated with water will be measured by applying a hydrostatic pressure difference across the specimen. The Darcy permeability will be determined by dividing the liquid flow rate by the pressure gradient and the cross-sectional area of the specimen.

*Liquid Diffusivity Calculations*. The liquid diffusivity is the fundamental transport property which when multiplied by the gradient in moisture content gives the moisture transfer rate within a material. The liquid diffusivity for the six materials will be calculated from the derivative of the capillary pressure with respect to moisture content, the liquid permeability, and other known properties.

**RECENT RESULTS**

Fanney, A. H., Thomas, W. C., Burch, D. M., and Mathena, L. R., "Measurements of Moisture Diffusion for Building Materials," *ASHRAE Transactions*, Vol. 97, Part 2, June 1991.

## MOISTURE TRANSFER MODEL FOR GENERATING MOISTURE GUIDELINES

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*Sponsor:* Department of Energy
Building Systems and Materials Division

**OBJECTIVE**

To develop a moisture property data base.

**PROBLEM**

During the winter season, the moisture content within buildings is considerably higher than the outdoor moisture content. As a result, water vapor permeates into walls and becomes absorbed within the outer layers of the wall. The accumulation of moisture within building materials has a profound effect on their thermal insulation properties. Mathematical models are not able to accurately predict the degree of moisture accumulation in the components of typical composite walls. As a result, costly experimentation is required because individual measurements cannot readily be extended to different wall geometries and different climates.

During FY 1990, the NIST Moisture Transfer Model was enhanced to include capillary transfer (i.e., transport by liquid water) and convection transfer (i.e., transfer by air infiltration and exfiltration). A computer program for the enhanced model was developed. This program is capable of predicting hourly

moisture content distribution within different multi-layer wall construction as a function of time. The program uses climate data from Weather Years for Energy Calculations (WYEC). This program was subsequently used to develop preliminary moisture control strategies for walls for inclusion in the DOE Moisture Handbook.

Reliable moisture property data needed as input for the NIST Moisture Transfer Model are unavailable in the literature. An examination of the moisture property data for each of common building materials reveals that 1) diffusion coefficients measured by different sources vary markedly, 2) capillary diffusivity data exist for only a few common building materials, and 3) sorption isotherms (i.e., moisture content versus relative humidity) and suction curves (i.e., capillary pressure versus moisture content) do not exist for many common building materials.

**APPROACH**

During FY 1991, BFRL will perform the following:

*Diffusion Coefficient Measurements*. A newly developed measurement technique will be used to determine the diffusion coefficient as a function of moisture content for ten common building materials. Separate measurements will be carried out at 24 °C and 6 °C (75 °F and 41 °F). Here a material specimen will be mounted in a modified ASTM permeance cup. Saturated salt-in-water-solutions will be used to generate small relative humidity differences across the specimen. As moisture is transferred through the specimen, the cup assembly will either lose or gain weight. The water vapor transfer rate through the specimen will be determined by periodically weighing the cup assembly. For each of the materials, standard ASTM wet and dry cup permeance measurements will also be performed and compared to the diffusion measurements.

*Sorption Isotherm Measurements*. Sorption isotherms will be measured for ten common building materials. Separate adsorption and desorption measurements will be carried out at 24 °C and 6 °C. Here small specimens of the materials will be sealed in jars above eight different saturated-salt-in-water solutions. Each specimen will be conditioned in a jar until its weight reaches an equilibrium value. After reaching equilibrium, the specimens will be removed from the jars and weighed on a precision balance. Their moisture content will be plotted versus relative humidity to produce sorption isotherms.

*Capillary Property Measurements*. A preliminary study will be carried out to develop measurement techniques suitable for determining the capillary diffusivity of building materials. A measurement technique originally developed for wood will be applied to other building materials. Here small specimens of a material will be saturated with liquid water, placed in a centrifuge, and spun at different rates. The suction pressure within the specimen will be correlated to the final moisture content of the specimens. In addition, the liquid water permeability of the material will be determined by imposing a water pressure difference across specimens saturated with water and measuring the resulting water flow rate. The capillary diffusivity may be obtained from the above two measurements. An effort will be made to apply this measurement technique to four common building materials.

*Variability of Moisture Property Data*. For all the above moisture property measurements, the data will be compared to existing data in the literature, thereby permitting the variability in the existing data to be assessed.

*Participate in DOE Moisture Research Panel*. BFRL will participate in the DOE Research Panel to provide technical guidance on the development of a handbook containing moisture control guidelines and a research agenda.

**RECENT RESULTS**

Burch, D. M., Thomas, W. C., Mathena, L. R., Licitra, B. A. and Ward, D. B., "Transient Moisture and Heat Transfer in Multilayer Nonisothermal Walls—Comparison of Predicted and Measured Results," *Proceedings of the ASHRAE/DOE/BTECC Conference, Thermal Performance of the Exterior Envelope of Buildings IV*, December 1989.

Thomas, W. C. and Burch, D. M., "Experimental Validation of a Mathematical Model for Predicting Water Vapor Sorption of Interior Building Surfaces," *ASHRAE Transactions*, Vol. 96, Part 1, January 1990.

## MOISTURE CONTROL IN MANUFACTURED HOUSING WALLS

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*Sponsors:* Department of Housing and Urban Development
Innovative Technology and Special Projects Division

Department of Agriculture
Forest Product Laboratory

**OBJECTIVE**

To corroborate field measurements of eight test walls exposed to outdoor winter conditions in Madison, WI using a mathematical model that predicts moisture accumulation in walls.

**PROBLEM**

Many moisture problems in homes during winter are a result of excessive indoor humidity. Recent damage in walls of manufactured homes in Wisconsin, Minnesota, and other Midwestern states was found to be primarily the result of excessive indoor humidity due to lack of ventilation. Conversely, results from previous research at the Forest Products Laboratory (FPL) indicate that flaws in design and/or workmanship are less likely to lead to moisture damage if indoor humidity is kept at moderate levels. However, too much uncertainty exists in projecting the effects of indoor relative humidity on moisture accumulation in walls for reliable application of current design techniques.

**APPROACH**

The FPL has been funded by the Department of Housing and Urban Development (HUD) to carry out a field study to investigate the effects of indoor humidity and wall construction on the moisture-related performance of manufactured housing walls. As part of this study, FPL will field expose eight test walls to outdoor climatic conditions at Madison, WI. Four of the test walls will be of different construction and will be tested with a moderate indoor relative humidity (approximately 35%). The other four walls will be identical to the previous four but will be tested with a high indoor humidity (50–60%). The moisture content of materials within these walls will be measured as a function of time. The effect of moisture on the heat transmission will be investigated.

BFRL has previously developed a complex mathematical model that predicts the time-dependent transfer of heat and moisture in multi-layer walls. The model is comprised of two coupled differential equations; namely, a conservation of mass equation and a conservation of energy equation. These equations are solved by the implicit finite-difference method.

This model will be extended as necessary to simulate the moisture and thermal performance characteristics of the eight test walls.

This work will be performed under 5 tasks:

1. *Calibration of Heat Flux Transducers*. NIST will provide and calibrate eight heat flux transducers for measuring the effect of moisture on the heat transmission.

2. *Transport Property Measurements*. NIST will measure the permeability and sorption isotherms of wall specimen materials for which transport property data is unavailable in the literature.

3. *Computer Predictions to Design Field Experiment*. Prior to the field experiments, NIST will use the mathematical model to predict the moisture performance of the eight walls. The predicted results will be used to assist in designing the experiments, including the determination of where instrumentation should be placed.

4. *Computer Predictions of Field Measurements*. FPL will provide NIST with floppy disks containing hourly measurements of indoor and outdoor temperature and relative humidity for the field measurements. Using these measurements as boundary conditions; NIST will use the mathematical model to predict the measured moisture content of the eight walls.

5. *Computer Predictions to Extend Field Measurements*. NIST will carry out computer predictions using the mathematical model to extend the field measurements to account for different indoor humidity conditions and outdoor climatic conditions.

This work will complement a field study being conducted by FPL. Once field results have been corroborated with BFRL's computer model, the model will be used to extend the field results to other climatic regions.

**RECENT RESULTS** New project in 1991.

## VENTILATION REQUIREMENTS FOR MANUFACTURED HOUSING

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***Sponsor:*** Department of Housing and Urban Development
Office of Policy, Development, and Research

**OBJECTIVE** To develop revised indoor and attic ventilation requirements for inclusion in the HUD "Manufactured Home Construction and Safety Standard."

**PROBLEM**

Field surveys indicate that mobile homes experience moisture problems such as window condensation and mold and mildew growth at interior wall surfaces. These problems are a direct consequence of insufficient indoor ventilation being provided to remove moisture generated by occupant related activities (i.e., cooking, bathing, occupant respiration, etc.).

The proposed HUD "Manufactured Home Construction and Safety Standard" requires a minimum indoor ventilation rate of 0.7 $m^3$ (25 $ft^3$) per minute and permits manufactured housing to have inoperable window systems. A preliminary analysis carried out by BFRL revealed that this required ventilation rate permits excessive indoor relative humidity that causes window condensation. When the outdoor temperature is above 10 °C (50 °F), the indoor relative humidity can potentially rise above 70%, thereby promoting fungus and mold growth at interior wall surfaces.

Reports from field surveys further indicate that the attics of some manufactured housing become wet, providing a potential for deterioration of the roof construction. This problem is believed to be a direct consequence of inadequate attic ventilation to remove moisture that enters the attic by way of diffusion and convective air movement from the living space.

There is a need to develop revised ventilation requirements for the indoor air and the attic of manufactured housing.

**APPROACH**

This work will be performed under two categories:

*Indoor Ventilation Requirements*. BFRL will perform a comprehensive analysis of the required ventilation rates that prevent window condensation and maintain the indoor relative humidity below 50%. The analysis will include single and double-pane windows. The analysis will include a wide range of outdoor climates including a mild heating climate (Atlanta, GA), an intermediate heating climate (Boston, MA), a cold heating climate (Madison, WI), a Gulf coast climate (Lake Charles, LA), and a Pacific northwest climate (Portland, OR).

In the analysis, a moisture balance on a typical manufactured home will be carried out. The predicted indoor ventilation rates will be correlated with respect to outdoor climate, thereby permitting the indoor ventilation requirements for a wide range of climates to be determined without the need for further analysis. In addition, the predicted indoor ventilation requirements will be compared to those given in the ASHRAE Ventilation Standard 62-1989. The recommended ventilation rates for the HUD Standard on Manufactured Housing will be values that prevent window condensation and meet the ASHRAE Ventilation Standard 62.

*Attic Ventilation Requirements*. BFRL recently developed a comprehensive moisture transfer model that predicts the temperature and moisture content in each layer of a building component as a function of time of year. The model is a distributed-capacity, finite-difference model that includes vapor diffusion, convection, and capillary transfer. It uses hourly weather data as input and can simulate the moisture performance of a wide range of different building constructions. This model has been experimentally verified by way of comparison to two different laboratory experiments.

The NIST Moisture Transfer Model will be used to simulate the thermal and moisture performance for three different attic constructions of manufactured housing. The climates analyzed will include a mild heating climate (Atlanta, GA),

an intermediate heating climate (Boston, MA), a cold heating climate (Madison, WI), a Gulf coast climate (Lake Charles, LA), and a Pacific northwest climate (Portland, OR). For these computer runs, the maximum temperature and moisture content of the roof sheathing of three attic constructions will be analyzed.

The results of this project will provide HUD with indoor and attic ventilation requirements for inclusion in their Mobile Home Construction and Safety Standard. In addition, for both tasks future research needs will be identified.

**RECENT RESULTS** New project in 1991.

## LONG-TERM THERMAL STABILITY OF FOAM-BLOWN INSULATING BOARDS

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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To assess the environmental and material factors adversely affecting the long-term, thermal performance of a foam-blown insulation board.

**PROBLEM** The thermal performance of foam-blown insulating boards changes over time as the thermal conductivity increases due to air permeation into the foam cells after manufacture. This change is rapid at first, but then slows down as it approaches a long-term equilibrium value. This equilibrium value is desired by architects in determining the thermal performance of the building envelope and eventually in sizing the heating and cooling equipment for a building.

In the past, this long-term equilibrium value has been estimated by exposing foam panels in laboratory tests to temperatures of 60 °C (140 °F). Recent results from field-exposed boards indicate, however, that the laboratory-obtained equilibrium value underestimates the true change in thermal performance of boards exposed outdoors. This indicates the need for additional knowledge on the interactions between the material and environmental factors which affect long-term thermal performance of foam boards.

**APPROACH** Diffusion of air into the foam and diffusion of chemical out of the foam are the main mechanisms responsible for the long term performance of foam-blown insulation. The primary element that affects the diffusion of gases in a foam is the cell wall. Physical and chemical properties of the cell wall may be changed as a result of exposure. These changes may be a result of increasing temperature thereby increasing free volume, or diffusion of chemical and water into the cell wall, both of which can plasticize the cell wall, thus enhancing the diffusion of air into the foam.

In 1990, BFRL completed the development of several analytical techniques for measuring physical, chemical, and thermal properties of cell walls of insulation foams. These properties include the glass transition temperature, chemical composition, modulus of elasticity, and morphology of the cell wall. We also developed a method for steady and transient thermal exposure of insulation foams.

Humidity is an important component of the outdoor exposure that may cause a difference in the thermal insulation property observed in the laboratory and the field. The research proposed will use the techniques developed in 1990 to 1) determine the effects of humidity on the physical and chemical properties of the cell walls, 2) relate these effects to the thermal insulation properties of the foam, and 3) to develop a physical-mathematical model to assess the effects of the humidity on the thermal performance of foam-blown insulation.

In 1991 BFRL will measure the physical and chemical properties of the cell wall and the thermal insulation of the foam as a function of humidity. Physical and chemical properties of the cell wall, and thermal insulation property of foam-blown insulation will be measured periodically on specimens that have been exposed to: 0, 50, 75 and 95% relative humidity at 60 °C. Since the diffusivity of oxygen and nitrogen through the insulation boards and the effects of humidity on the diffusion of these gases will be required in the development and validation of the model, an apparatus to measure the diffusion of these gases through the foam will be constructed in FY 1992.

BFRL's research in 1992 will concentrate on studying the effects of humidity on the diffusion of gases through the foam and the development of the model. The model will taken into account both material and heat transport diffusive processes obeying Fick's and Fourier's laws.

**RECENT RESULTS**

Zarr, R. R. and Nguyen, T., "Effect of Environmental Exposures on the Properties of Polyisocyanurate Foam Insulation: Thermal Conductivity Measurements," *Proceedings of 2nd International Workshop on the Long-Term Thermal Performance of Cellular Plastics*, June 1991.

## THERMAL RESISTANCE MEASUREMENTS OF FOAM INSULATION PRODUCTS USING THE GUARDED HOT PLATE AND THE HEAT FLOW METER

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*Sponsor:* Department of Energy
Building Systems and Materials Division

**OBJECTIVE**

To examine the effect of different conductivity and thickness of materials in calibrating a small heat-flow-meter apparatus ASTM C518.

**PROBLEM**

For the measurement of thermal conductivity, the apparatus of choice for the majority of foam manufacturers is the heat flow meter. The heat flow meter is a relative apparatus in that it requires a specimen measured with the guarded hot

plate for calibration. Thermal measurement laboratories generally determine the calibration coefficient for their heat flow meter apparatus using certified standards from a national laboratory. The Office of Standard Reference Materials at NIST offers three Standard Reference Materials (SRMs 1449, 1450b, and 1451) for the calibration of heat-flow-meter apparatus. Of the three, SRMs 1449 and 1450b are most suited for calibrating the heat flow meter when foam products are to be measured.

Fumed-silica board, SRM 1449, provides a low conductivity (0.021 W/m·K), comparable to insulation foams blown with chlorofluorocarbon (CFC) blowing agents. Fibrous-glass board, SRM 1450b, has a conductivity of 0.030 W/m·K. Thermal measurement laboratories have expressed concerns in the accuracy of a heat-flow-meter measurement for a material of different conductivity or thickness than the calibration standard. NIST proposes extending the present comparison study with its one-meter guarded hot plate to a small commercially available heat flow meter using fumed-silica board, fibrous-glass board, extruded polystyrene, unfaced polyisocyanurate, and a high conductivity material such as gum rubber.

**APPROACH**

This project is an extension of the previous GHP/HFM (Guarded Hot Plate/Heat Flow Meter) project. A small heat-flow-meter apparatus (ASTM C518) will be obtained from a member of the NIST foam advisory panel. This apparatus has a plate size of $0.3 \times 0.3$ m ($1 \times 1$ ft), about one-half the size of a large heat-flow-meter apparatus.

Specimens from the previous HFM/GHP project will be selected and cut to size. The small heat-flow-meter apparatus will be calibrated using SRMs-1449 and 1450b at a mean specimen temperature of 24 °C (75 °F). Measurements of SRM-1449, fumed-silica board, will be adjusted to a common pressure of 101.3 kPa using results from previous measurements of the material.

To examine the effect of different conductivities on a heat flow meter measurement, NIST will perform comparison measurements at 24 °C with 25 mm (1 in) thick, specimens of extruded polystyrene, unfaced polyisocyanurate, and gum rubber. To examine the effect of specimen thickness in the calibration of a heat flow meter, NIST will perform comparison measurements with different thicknesses of extruded polystyrene and unfaced polyisocyanurate at 24 °C. The thickness of the foam products will be 25 mm, 37.5 mm, 50 mm, and 75 mm (1, 1.5, 2 and 3 in).

**RECENT RESULTS**

Zarr, R. R. and Somers, T. A., "Thermal Conductivity of Fumed-Silica Board, SRM-1449, at Room Temperature," *Proceedings of the 21st International Thermal Conductivity Conference*, October 1989.

Zarr, R. R., "Summary of Low-Density Glass-Fiber Reference Materials at NIST 1980-1989," *The Journal of Thermal Insulation*, Vol. 14, pp. 211–220, January 1991.

Zarr, R. R. and Licitra, B. A., *Calibration at 24 °C of a Heat-Flow-Meter Apparatus Having 610 mm Square Plates*, NISTIR 91-4539, April 1991.

# ROUND-ROBIN TESTING PROGRAM FOR LOOSE-FILL THERMAL INSULATION

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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To measure the thermal resistance of four loose-fill and one batt insulations as part of the second round of the ASTM C-687 Round Robin.

**PROBLEM** Round one of the ASTM C687 Round Robin was completed in 1987 and the results were used in the precision and bias statement of ASTM C687 88 Revision. The measurements indicated the capability of the participants was characterized by an imprecision of 21% for cellulose, 14% for bonded glass-fiber, 16% for unbonded glass-fiber and 10% for rock/slag wool. The capability of participants to measure a specimen of 0.15 m (6 in) glass-fiber batt, however, was 3% The large variation for the loose-fill materials was attributed primarily to inadequately defined procedures for preparing and conditioning specimens. A second round for interlaboratory comparison of loose-fill materials was organized by ASTM Committee C16 and NIST was requested to participate.

**APPROACH** Four loose-fill materials and one glass-fiber batt have been selected for testing in the second round of the ASTM C-687 Round-Robin. Of the four loose-fill materials, three 'Rockwool,' 'Insulsafe III,' and 'Cellulose' must be applied by a pneumatic blower machine. To prepare specimens of these materials, NIST will contact the National Association of Home Builders Rssearch Center (NAHBRC), MD to blow these specimens with their pneumatic blower. These specimens will be hand-carried from NAHB to NIST. The fourth loose-fill material 'Perlite' will be prepared onsite. All specimens will be prepared for measurement at a thickness of 0.15 m.

Measurements of the five materials will conducted using the BFRL one-meter guarded hot plate. The apparatus will be operated in a one-sided mode of operation with heat flow in the upward direction. Measurements will be conducted at a mean specimen temperature of 23 °C (73 °F) with a temperature difference of 28 °C (82 °F) across the thickness of the specimen. BFRL is the national reference source for a major round-robin test program evaluating ASTM Standard C687.

**RECENT RESULTS** New project in 1991.

# LIGHTING TECHNOLOGY

# EVALUATION OF LUMINANCE DISTRIBUTIONS

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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop and evaluate measurement procedures for assessing the distribution or pattern of luminances in office spaces, as part of an on-going effort in developing techniques for evaluating lighting quality.

**PROBLEM** Recent publications by Collins, Gillette, Fisher and Marans (1989) and Collins (1990) reported that certain lighting system configurations, specifically fixed task lighting combined with an indirect ambient lighting system, were associated with higher energy use (in terms of lighting power density), and higher illuminances, but lower ratings of lighting satisfaction than a comparable situation in which direct ambient lighting provided the primary illumination. Analysis of the photometric data suggested that the average luminance for the task indirect lighting system was much lower, being about 25–50% of that for the direct system. This analysis provided some insight into why occupants consistently rated these spaces as "dim" even though their task illuminances were within IES guidelines and comparable to those measured for the direct system.

This research suggests the importance of luminance distribution in the perception of the lighting quality in a space. It does not, however, provide precise measures of either the luminance distribution nor the associated occupant response. The luminance mapping device recently acquired by BFRL provides the capability for more comprehensive and precise measurements of luminance distributions than was possible in the data reported by Collins et. al. (1989). Such measurements must then be related to occupant response in a meaningful fashion.

Previous BFRL research consisted of point-by-point luminance measurements and development of a framework for characterizing the luminance distribution and potential task visibility within the space, for relatively uniformly-lit spaces. This research will extend measurements of the luminance distribution by several orders of magnitude, allowing a more comprehensive assessment of visibility and occupant response conditions in a variety of different lighting conditions.

**APPROACH** The reliability and validity of the luminance mapping device will be evaluated in a round-robin series of photometric measures with the National Research Council of Canada (NRC) and the Building Research Establishment (BRE) of the U.K. The performance of the mapping device will be compared against that of a laboratory quality photometer for a series of known targets. Inter-instrument and inter-laboratory comparisons will be made. Following this evaluation, the performance of the device will be evaluated for three different lighting configurations in real offices. Procedures for measuring luminances in real offices will be developed and evaluated for different lighting configurations.

In the second phase of the project the measurement of luminance distributions will be combined with subjective evaluation to assess the role of variations in luminance distributions on the perception of lighting quality. An experiment will be carried out to test the hypothesis that the combination of low average room

luminance with high task illuminance results in lower perceived lighting quality than the same situation with greater average room luminance. Detailed measurements of room luminance will be made with the luminance mapper, while subjective response will be assessed using scaling techniques.

The development of the capability of assessing luminance distributions and their impact on lighting quality is one further step toward the goal of a reliable lighting quality metric.

**RECENT RESULTS**

Collins, B. L., Evaluation of the Role of Luminance Distribution in Occupant Response to Lighting. *Proceedings of the National Lighting Conference*, CIBSE, London, pp. 1–11, April 1990.

Collins, B. L., Fisher, W. S., Gillette, G. L. and R. W. Marans, "Second-Level Post-Occupancy Evaluation (POE)," Analysis Paper *Journal of the Illumination Engineering Society*, Vol. 19, pp 21–44 (Summer 1990).

Collins, B. L., "The Psychological Aspects of Lighting: A Review of the Work of CIE TC 3.16," *Proceedings of PA State University Symposium on Psychological Aspects of Lighting*, January 1991.

## ASSESSMENT OF LIGHTING TECHNOLOGY IN FEDERAL OFFICE BUILDINGS

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***Sponsor:*** General Services Administration
Public Buildings Service
Office of Real Property Development

**OBJECTIVE**

To assess current lighting technology and the GSA design process for Federal office buildings, with detailed information on selecting and implementing sources, luminaires, ballasts, and relevant office furnishings to maximize energy efficiency without sacrificing user acceptance and productivity.

**PROBLEM**

GSA is concerned about occupant complaints about low lighting levels in some Federal office buildings. Measured illuminance levels in these buildings are below IES recommendations for office lighting. While the design is intended to provide at least 538 lx (50 fc) on the working plane, the reality always seems to be less. In addition, recent experience has suggested that the addition of systems furniture with fixed task lighting also creates unsatisfactory lighting for many office tasks with illuminance levels well below current recommendations. The standards, criteria and guidelines for lighting design in GSA facilities do not appear to be adequate or effective. As a result, there is a need for accurate information on system and component performance as input for lighting design guidelines for federal office buildings, as well as for detailed information on selecting and using energy efficient sources, luminaires, ballasts, and relevant office furnishings to maximize energy efficiency without sacrificing user acceptance and productivity.

**APPROACH**

This research will evaluate the effectiveness of current specifications used by GSA and others; evaluate specific lighting components and systems; and provide an assessment and recommendations to GSA on lighting component and system performance. A multi-phase activity over several years is planned.

During the first year, work will involve assessing existing design criteria, test procedures, and evaluation processes; determining hardware and system performance; data-base development; and laboratory research. BFRL will review existing specifications, procedures, and calculations, for lighting in terms of energy conservation, typical hardware, lighting levels, task performance, and user acceptance. Current industry design applications and recommendations for office lighting including both national and international recommendations will be reviewed.

BFRL will expand its laboratory facilities for research on lamp component and lighting system interactions. This will allow lighting hardware components and system designs to be evaluated in a semi-realistic office setting. Early in the project, BFRL will develop a matrix of lighting design components and systems to be evaluated. Likely candidates for evaluation include ballast technologies such a conventional, energy efficient, and electronic ballasts; tube designs such as T-8, T-12, and U-shaped; lamp phosphors such as cool white, tri-phosphor, and other enhanced phosphors; fixture designs such as lenses, parabolic louvers, and conventional louvers; and ceiling layout. The performance of several innovative systems will be compared against one or more standard configurations currently used by GSA.

BFRL will assess the design process used to specify lighting systems in GSA buildings. The role of interior furnishings, including systems furniture and space layout, will be assessed. The procedures used by GSA in the design process will be identified, with particular emphasis placed on unanticipated interactions between different aspects of the system. A report will be published describing the results of specific lighting system performance, and the assessment of the current lighting process used by GSA.

In subsequent years, BFRL will evaluate actual applications of lighting designs in GSA facilities, using techniques such as case history assessment, post-occupancy analysis, an full-scale room evaluations. It will determine where success and failure occurs. This information will be used as input for revisions to the design process used by GSA and could include the development of new design guidelines. This project will enable GSA to have guidelines for design of lighting systems and selection of sources, luminaires, and ballasts.

**RECENT RESULTS**

New project in 1991.

# LIGHTING AND HVAC INTERACTION RESEARCH PROJECT

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*Sponsor:* Department of Energy
Building Systems and Materials Division

**OBJECTIVE** To develop improved evaluation methods and design tools to enable the design and operation of efficient lighting and HVAC systems in commercial buildings, along with strategies to control peak cooling loads due to lighting.

**PROBLEM** Lighting constitutes a substantial portion of commercial building electrical energy usage, typically ranging from 25 to 50%. Most of the energy dissipated to the building space eventually contributes to building cooling load. Due to the temperature dependence of fluorescent lighting power consumption and light output, there are significant interactions between the lighting and HVAC systems. As a result, lighting system light levels and efficiency, and cooling loads due to lighting, can vary substantially due to lighting and HVAC system design and operation. Previous results have indicated performance variations of up to 20% are possible.

These effects influence the number of luminaires required to provide the design illumination levels and the size of HVAC equipment to meet the cooling loads contributed by the lighting system. This, in turn, influences the first cost of the lighting and HVAC systems, and the operating costs for energy, including demand charges for electrical power usage during peak periods. Such peak period power usage puts added pressure on electrical utilities to meet system-wide power demand by increasing generating capacity.

**APPROACH** The interactions between lighting and HVAC systems in commercial buildings are being investigated through a combination of full-scale measurements and computer simulations. The results are being analyzed to provide the technical basis for design procedures and methods, which are also being developed, with assistance from Ross and Baruzzini under contract to EPRI.

Full-scale measurements are being conducted at the BFRL for various lighting system, HVAC system and room configurations and operating conditions. Lighting system performance, thermal loads and energy transfers are monitored to enable determination of optimum operating conditions and strategies.

A detailed computer model is being developed and verified using the measurement results. The model will be used to extend the results to a wide range of configuration so that the design guidelines will be more general and comprehensive. The computer model will serve as a stand-alone design tool, but will also be the basis of a sub-routine to operate with larger building energy analysis computer programs such as BLAST and DoE-2. This will provide such programs with the capability of evaluating the interactions between the lighting and HVAC systems, a sensitivity which they currently lack.

ASHRAE and IES are revising their Handbooks of Fundamental Data. BFRL's report on this work will contain revised weighing factors and the rationale for their revision which will be designed for inclusion in the ASHRAE Handbook.

BFRL, too will explore possible revisions to the Lamp Section of the IES Handbook and/or development of a document which could be used as an IES recommended practice on lamp temperature interaction. Both efforts will assist in translating BFRL results to the appropriate design and research communities.

**RECENT RESULTS**

Treado, S. J., "The Effect of Building Envelopes on Cooling Loads Due to Lighting," *Proceedings of the ASHRAE/DOE/BTEEC Conference. Thermal Performance of the Exterior Envelope of Buildings IV*, December, 1989.

Treado, S. J. and J. W. Bean, "Experimental Evaluation of Lighting/HVAC Interaction," *ASHRAE Transactions*, Vol. 96, Part 2, June 1990.

Treado, S. J., *Program Plan for Comprehensive Illumination Model*, NISTIR 89-4222, July 1990.

Walton, G. N., *A Computer Program for Simulation of HVAC/Lighting Interactions: Initial Report*, NISTIR 90-4472, December 1990.

Treado, S. J. and J.W. Bean, *Measurement and Evaluation of Lighting/HVAC Interaction*, NISTIR 90-4429, April 1991.

## OPTICAL PERFORMANCE OF COMMERCIAL WINDOWS

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*Sponsor:* Security Evaluation Office

**OBJECTIVE**

To identify and evaluate commercially available window systems relative to their ability to protect against optical security threats.

**PROBLEM**

The traditional purpose of building fenestration systems, including windows, skylights and clerestories, is to admit daylight to building interior spaces and to allow building occupants a view of the outside. Important performance characteristics of fenestration elements include transmittance, reflectance, and refraction as functions of wavelength, along with thermal transmittance, structural integrity and long-term durability. Usually, the interest in window performance relates to the transfer of solar energy or visible light from the exterior environment to the building interior. However, windows can allow the transmission of visible light in either direction, thus affording a view into a building under some conditions. This can present security problems due to unwanted visual access to building interiors. On the other hand, the elimination of windows has undesirable effects on building occupants and the quality of the workplace. In this context, it would be desirable to have a window which would allow the building occupants to see outdoors without compromising the visual security of the building. A related optical threat associated with windows is the potential for information to be obtained via use of lasers.

Durability, or more precisely, the stability of window performance characteristics over extended periods of time exposed to exterior solar and environmental conditions is another concern. Weathering and/or aging may degrade the performance

characteristics of a window system to the point that it is no longer acceptable. It is important to be able to predict or prevent this occurrence and to periodically verify compliance.

**APPROACH**

During FY 1990, BFRL will perform:

1. Identify important relevant window performance characteristics and testing procedures. The specific optical properties of windows and their influence on optical security will be evaluated. The test procedures and equipment required to evaluate these properties will be determined. A literature search will be performed.

2. Survey commercially available windows and window treatments. A comprehensive survey of currently available window systems and materials will be conducted. Manufacturers' performance specifications will be obtained.

3. Select the appropriate window candidates according to the desired performance characteristics. The characteristics of the available window systems will be compared to the desired characteristics, and promising window candidates will be identified and obtained.

4. Evaluate and test the window candidates to determine their complete performance characteristic profiles. The window candidates will be tested to more fully characterize their performance and to verify manufacturers claims. Detailed laboratory measurements of the spectral optical properties will be conducted covering all important wavelengths. The effect of various lighting conditions on the transmission of visible information will be evaluated.

5. Rate the window candidates and compile the results. The results of the evaluation will be compiled to allow comparison of the performance of various window systems, including their relative strengths and weaknesses.

6. Prepare a technical report describing the results of the survey, testing and evaluation, including manufacturers, availability and pricing. The report will summarize all of performance characteristics including energy, durability and structural considerations.

7. Perform follow-up testing to document and verify actual field performance both immediately following installation and at periodic intervals to monitor any changes due to weathering or aging.

The results of this work will assist the SEO assess window technology for use in their security facilities.

**RECENT RESULTS**

New project in 1991.

# EVALUATION OF LIGHTING AND OTHER AIDS TO RECOGNITION OF TOP MARKS AND BUOY SHAPE INDICATORS

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*Sponsor:* U.S. Coast Guard
Research and Development Center (Avery Point)

**OBJECTIVE** To evaluate the research literature on the effectiveness of various types of topmarks and buoy shapes as aids to navigation under different ambient lighting conditions.

**PROBLEM** The IALA Guidelines for the Maritime Buoyage System are currently being considered for adoption by the U.S. Coast Guard. Implementation of these guidelines represents a substantial departure from current practice that will be difficult to justify unless information on the effectiveness of these markings is obtained. Such information includes the conditions under which detection, recognition, and identification is improved or worsened by the marker. Marker characteristics to be evaluated include color, shape, luminance, illumination, height, and visual angle. In addition, the evaluation will also include an assessment of foreign standards and regulations such as the IALA documents, to determine areas of agreement and conflict. The research base for the current IALA standards for maritime buoyage and topmarks is not adequately specified. Further information is needed on the characteristics such luminance, color, uniformity, and overall visibility of such markers which determines their detection, recognition, and identification under a variety of external ambient lighting conditions.

**APPROACH** During FY 1991, BFRL will perform this work in three tasks:

1. Conduct a literature search on research into detection, recognition, and identification of colors and shapes under different natural lighting conditions and distances will be assessed. Based on this review, develop a plan with procedures for evaluating the parameters of topmarks and shapes. This plan will be designed to answer questions about the effectiveness of markings which have arisen during the course of the literature review.

2. Assess the effectiveness of different types of markers under different lighting conditions. This work will be assessed, most likely in a laboratory simulation experiment using Coast Guard personnel.

3. Author a final report that summarizes previous research in detection, recognition, and identification of colors and shapes, and the findings from this research project.

**RECENT RESULTS** New project in 1991.

# TEST PROCEDURES FOR EQUIPMENT ENERGY USE

# HEAT PUMP AND AIR CONDITIONER TEST PROCEDURES

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*Sponsor:* Department of Energy
Office of Codes and Standards

**OBJECTIVE** To provide industry, through the Department of Energy (DOE), with an equitable testing and rating procedure for determining the seasonal energy performance of central residential air conditioners and heat pumps.

**PROBLEM** The Energy Policy and Conservation Act (PL Act 94 163) (EPCA), as amended, requires DOE to prescribe test and rating procedures and minimum performance standards for various residential appliances. In addition, the 1987 amendments to EPCA requires analysis of any test procedure amendments to determine their effect on minimum efficiency standards. DOE has, since 1975, relied on BFRL to develop test and rating procedures.

**APPROACH** BFRL has completed rating procedures for mixed air conditioners and heat pumps where components are manufactured by different companies and assembled in the field, e.g., replacement of an outdoor unit with an old indoor coil intact, or new installations with indoor and outdoor units from different manufacturers. The methodologies cover the cooling and the heating mode. BFRL will complete a technical paper describing the background of the development of the mixed rating procedure in the heating mode.

BFRL will develop a revised DOE test procedure for central heat pumps and air conditioners that references the latest ASHRAE and ARI Standards and includes: the same amount and type of information on cooling as currently exists on heating, a modification of the progression from single speed to two-speed and to variable speed equipment so it is consistent from section to section, new sections to handle heat pumps which do not have the capability to defrost, and appropriate language to cite an entirely new appendix on integrated heat pump water heating appliances.

Since 1985, BFRL has participated in ASHRAE Standard Project Committee 116 developing a consensus standard for the evaluation of the seasonal performance of air-conditioners and heat pumps. BFRL will continue its participation which will include review and response to public comments, and preparation of the final version of the standard. The participation will enable BFRL and DOE to have the latest information and suggestions from the industry for updating the Federal Test Procedure.

BFRL will assist DOE review petitions for waivers from the Federal Test Procedure for air conditioners, heat pumps, and refrigerators. Petitions are expected to come from U.S. manufacturers requesting credits for new features in their product and from foreign manufacturers whose equipment cannot be tested according to the Federal Test Procedures. BFRL also will evaluate petitions submitted by manufacturers for rating procedures for mixed systems and provide recommendations to DOE whether they are technically acceptable.

**RECENT RESULTS**

Domanski, P. A., "Simulation of an Evaporator with Nonuniform One-Dimensional Air Distribution," *ASHRAE Transactions*, Vol. 97, Part 1, January 1991.

Domanski, P. A., "Rating of Mixed, Split, Residential Heat Pumps Operating in the Heating Mode," *ASHRAE Transactions*, Vol. 97, Part 2, June 1991.

Aaron, D. A. and P. A. Domanski, "Experimentation, Analysis and Correlation of R-22 Flow Through Short Tube Restrictors," *ASHRAE Transactions*, Vol. 96, Part 1, January 1990.

Domanski, P. A., *Rating Procedure for Mixed Air-Source Unitary Heat Pumps Operating in the Heating Mode*, NISTIR 90-4298, May 1990.

## TEST METHODS FOR HEAT PUMPS AND AIR CONDITIONERS INTEGRATING THERMAL ENERGY STORAGE AND HEATING

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*Sponsor:* Electric Power Research Institute

**OBJECTIVE**

To develop a method for simulating residential central heat pumps with integral thermal storage and use the simulation to investigate ways to test and rate the unit.

**PROBLEM**

During the past several years, electric utilities are offering demand-side management programs to their residential and commercial customers. These programs are offered as the gap between electricity supply and demand narrows from delays in construction of new power plants due to financing, regulatory, and environmental issues.

Unitary heat pumps with integrated heat and cool storage could play an important part in electric utility residential demand-side management programs by shifting some of the on-peak electric demand to off-peak periods. These systems are in the emerging technology stage. Each manufacturer has a unique hardware design and a unique control strategy.

The DOE-approved testing and rating procedures for single and variable speed heat pumps and air conditioners and domestic water heaters are followed by industry organizations as ARI and GAMA in rating their equipment. Each added function (e.g., water heating coupled with space conditioning) tends to add complexity to the analysis and measurement procedures and renders the comparison of performance of various manufacturers' equipment in terms of the conventional efficiency measures difficult. Load management functions add another dimension of information requirements—the need for performance indices that reflect the demand reduction and electrical energy shifting capabilities of the thermal storage systems.

**APPROACH**

BFRL will perform this work in five Tasks:

1. Survey existing public-domain and licensable or purchasable computer programs for simulating heat pump, air conditioner, thermal energy storage system and water heater capacity, and power demand (e.g., HPEAK, TESCOMP, TRNSYS, EPRI's water heater codes now under development, and others) as a basis of computer model development. BFRL will review technical literature and other information on the performance parameters, operating modes, and control schemes of IHPs on the market or in the advanced development stage. If required, BFRL will contact or visit selected (two or three) manufacturing or installation sites.

2. Develop a general flow chart for the proposed simulation model, identifying the major submodels and subroutines and the general computational sequence.

3. Develop detailed work plan for program development and validation, including task and major subtask schedules and timing of outputs (deliverables).

4. Write and test computer code in conformance with the program outline of task 3. Document written computer code on a running (daily) basis; i.e., maintain a glossary of constants and variable names, constant values used as parameters, names of input and output files, functions and subroutines, flags, loop parameters, etc., to allow "outside" parties to understand the code.

5. Develop work plan for laboratory benchmark testing and simplified testing and rating method development.

The results of this project will remove a potential barrier to the sales of a new central heating and cooling project developed by EPRI.

**RECENT RESULTS** New project in 1991.

## A RATING METHOD FOR INTEGRATED HEAT PUMP-WATER HEATERS

*Principal Investigator:* Brian P. Dougherty
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*Sponsor:* Department of Energy
Office of Codes and Standards

**OBJECTIVE** To provide equitable testing and rating procedures for determining the energy performance of integrated heat pump water heaters.

**PROBLEM** The Energy Policy and Conservation Act (PL 94-163) (EPCA), as amended, requires the Department of Energy (DOE) to prescribe test and rating procedures and minimum performance standards for various residential appliances. In addition, the 1987 amendments to EPCA requires analysis of any test procedure amendments to determine their effect on minimum efficiency standards. DOE has, since 1975, relied on BFRL to develop the test and rating procedures.

**APPROACH** On April 11, 1990, DOE granted the Carrier Corporation a test procedure waiver for rating its HydroTech 2000 integrated heat pump/water heating (HP/WH) appliances. This test procedure specifically addresses the features of the Carrier product: variable speed compressor and indoor fan, water-source defrost, and full condensing water heating. At approximately the same time, BFRL began testing a Carrier HydroTech 2000 in one of its laboratories. Using the test procedure waiver and laboratory findings as starting points, BFRL will develop a proposed test procedure that covers all types of integrated HP/WH appliances. This work will be used by DOE in preparing a rule making for updating and expanding the existing air-source heat pump test procedure to include integrated appliances.

During FY 1991, tests will be conducted to determine the repeatability of the tank recovery tests and the effect of using different water heaters for these tests. In addition, new laboratory tests to evaluate four different methods for determining capacity and power usage data when operating in a water heating mode will also be conducted. The need for evaluating these test methods stems from having packaged integrated HP/WH appliances where the water piping between the refrigerant-to-water heat exchanger and the water heater is inaccessible or where the refrigerant-to-water heat exchanger is actually inside the water heater. For such appliances, an alternative test method where the water heater is connected will be required. Three of the four methods to be tried are of this type. The fourth method, which has been used exclusively thus far, involves having constant temperature water supplied to the inlet of the refrigerant-to-water heat exchanger and the water heater physically disconnected. As the needs arise, additional tests will be conducted.

BFRL staff are active in the ASHRAE and ARI committees that are developing testing and rating standards for integrated heat pump/water heating appliances e.g., the first working draft of ASHRAE Standard 137P. BFRL will conduct newly-proposed laboratory tests that will aid the progress of the committee. The scope of the ASHRAE Standard will initially be limited to covering heat pumps having a desuperheater and exclude appliances having a full condensing water heating capability like the HydroTech 2000.

**RECENT RESULTS** Dougherty, B., *A Proposed Methodology for Rating Integrated Air-Source Heat Pumps*, EPRI CU 6813 Project 2033-26 Final Report, April 1990.

## WATER HEATER TEST PROCEDURES

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*Sponsor:* Department of Energy
Office of Codes and Standards

**OBJECTIVE** To provide equitable testing and rating procedures for determining the energy performance of conventional water heaters.

**PROBLEM** The Energy Policy and Conservation Act (PL 94 163) (EPCA), as amended, requires the Department of Energy (DOE) to prescribe test and rating procedures and minimum performance standards for various residential appliances. In

addition, the 1987 amendments to EPCA requires analysis of any test procedure amendments to determine their effect on minimum efficiency standards. DOE has, since 1975, relied on BFRL to develop the test and rating procedures.

Heat pump water heaters are tested in accordance with a draft Gas Appliance Manufacturers Association (GAMA) test method. The test results are published in GAMA's Consumers Directory of Certified Water Heater Efficiency Ratings. The proposed DOE test procedure for water heaters includes provisions to test heat pump water heaters, however, no tests have been conducted to evaluate the proposed procedure.

**APPROACH**

BFRL will perform the following three tasks.

1. Evaluate the proposed DOE water heater test procedure for heat pump water heaters to anticipate issues which may arise when the industry begins to use the proposed procedure.

2. Evaluate the influence of relative humidity and ambient temperature on thermal performance. The resulting data will be used to quantify the degree of control required to insure repeatability.

3. Determine the influence of draw profile on performance of heat pump water heaters. It is anticipated that the draw profile will have a major influence on the energy factor of heat pump water heaters. The tests will be conducted to quantify the influence of the draw profile on the measured energy factor.

BFRL will assist DOE review petitions for waivers from the Federal Test procedure. A report on off-peak water heaters will be published during 1991.

**RECENT RESULTS**

Fanney, A.H., "The Measured Performance of Residential Water Heaters using Existing and Proposed Department of Energy Test Procedures," *ASHRAE Transactions*, Vol. 96, Part 1, January 1990.

## MONITORING OF AN ADVANCED VARIABLE SPEED INTEGRATED HEAT PUMP/WATER HEATING APPLIANCE

***Principal Investigator:*** A. Hunter Fanney
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***Sponsor:*** Allegheny Power Systems and
Potomac Edison Company

**OBJECTIVE**

To instrument and monitor a field installation of a Carrier variable-speed integrated heat pump/water heating appliance.

**PROBLEM**

The Carrier HyrdoTech 2000 variable-speed, integrated heat pump/water heating appliance incorporates several innovations. The compressor is packaged so its noise level approaches a conventional refrigerator. The variable-speed components, indoor humidistat, and smart controller permit enhanced temperature and humidity control.

BFRL proposed an elaborate testing and rating procedure for this type of heat pump in a project being conducted in parallel for DOE and EPRI. The procedure involves approximately 20 laboratory tests and a calculation procedure using a modified bin technique. This field experiment will provide unique data for BFRL to validate the proposed testing and rating procedure.

**APPROACH**

The thermal performance and the electrical energy usage of the system will be monitored over a twenty-four-month period. The influence of the appliance on peak demand loads of the Potomac Edison Company will be determined. The data will be compared with data from laboratory tests at BFRL on a similar unit and the results used to validate a proposed testing and rating procedure developed in a companion project being conducted for DOE.

BFRL will instrument the heat pump installation, develop appropriate software to reduce the experimental data, and report on the following:

1. Monthly heat pump electrical energy usage in the cooling mode, peak value and associated time of occurrence, and value at APS monthly peak.

2. Monthly heat pump electrical energy usage in the heating mode, peak value and associated time of occurrence, and value at APS monthly peak.

3. Coefficient of performance for the heat pump system (including and excluding supplemental heat used for space and water heating), maximum and minimum values during the month and their associated time of occurrence, and value at APS monthly peak.

4. Monthly water heater electrical usage, peak value and associated time of occurrence, and value at APS monthly peak.

5. Monthly supplemental heater energy consumption, peak value and associated time of occurrence, and value at APS monthly peak.

6. Monthly quantity of energy delivered to the water heater from the Hydro-Tech 2000 while operating in a combined mode.

7. Monthly quantity of energy delivered to the water heater while operating in a dedicated water heating mode.

8. Monthly average indoor and outdoor ambient temperatures.

9. Monthly average water main temperature.

10. Monthly gallons of hot water consumed.

In addition to the monthly values, hourly data will be recorded and stored on floppy disks and forwarded to Potomac Edison on a monthly basis.

The results of this project will provide in field performance data on a new Carrier Product for Allegheny Power Systems and determine the correlation with predicted performance based on a proposed laboratory test procedure.

**RECENT RESULTS**

New project in 1991.

# FURNACES, BOILERS, AND HOUSEHOLD HEATER TEST PROCEDURES

*Principal Investigator:* E. Kelly
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*Sponsor:* Department of Energy
Office of Codes and Standards

**OBJECTIVE** To provide equitable testing and rating procedures for determining the energy performance of central residential furnaces, boilers, and household heating equipment.

**PROBLEM** The Energy Policy and Conservation Act (PL 94 163) (EPCA), as amended, requires the Department of Energy (DOE) to prescribe test and rating procedures and minimum performance standards for various residential appliances. In addition, the 1987 amendments to EPCA requires analysis of any test procedure amendments to determine their effect on minimum efficiency standards. DOE has, since 1975, relied on BFRL to develop test and rating procedures.

**APPROACH** In FY 1991 BFRL will perform the following tasks:

1. Obtain and test a furnace employing power venting. Use the results of these experiments to refine the optional tracer gas procedure for measuring the off-cycle losses associated with central furnaces and boilers.

2. Conduct research to assist ASHRAE SPC 103 perform corrections and future refinements to the Furnace Test Procedure, including the use of flue dampers, testing "tight" and "inverted" units with tracer gas, determine the true effect of jacket losses in Isolated Combustion System applications, evaluate the performance of units with long post-purge times, and correct problems and inconsistencies in the annual fuel utilization calculation procedure. Develop recommendations for changes and extensions to the ASHRAE standard that need to be included in any DOE test procedure that references the ASHRAE Standard.

3. Develop a new DOE test procedure for furnaces and boilers that references ASHRAE Standard 103-1988 and proposed ASHRAE Standard 124P and includes: refined tracer gas test method for measuring off-cycle losses, a calculation procedure for determining the combined annual efficiency for combined space/water appliances, a rating methodology for units with inlet dampers, various changes resulting from known problems in both ASHRAE Standards, modifications made to the previous DOE test procedure in response to Request for Waivers from manufacturers, and an analysis of the effect of various waiver changes on proposed minimum efficiency standards for furnaces and boilers.

4. Carry out simulation studies on the annual performance and annual cost of operation of various types of combination space/water heating appliances and publish the results as an ASHRAE Technical or Symposium paper.

5. Assist DOE prepare responses to Request for Waivers and draft Federal Register Notices of Proposed Rule Making concerning the Furnace Test Procedure, including evaluating possible adoption of the ASHRAE Standard for inclusion in the DOE Test Procedures.

**RECENT RESULTS**

Liu, S. T., Kelly, G. E., and Terlizz, C. P., Experimental *Study on the Performance of Combination Appliance for Domestic Water and Space Heating*, NISTIR 90-4356, August 1990.

## LIGHTING FIXTURES AND SYSTEMS

*Principal Investigator:* J. Treado
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*Sponsor:* Department of Energy
Office of Codes and Standards

**OBJECTIVE**

To provide equitable testing and rating procedures for determining reduction of energy consumption for lighting in commercial facilities.

**PROBLEM**

The Energy Policy and Conservation Act (PL 94-163) (EPCA), as amended, requires the Department of Energy (DOE) to prescribe test and rating procedures and minimum performance standards for various residential appliances. In addition, the 1987 amendments to EPCA requires analysis of any test procedure amendments to determine their effect on minimum efficiency standards. DOE has, since 1975, relied on BFRL to develop test and rating procedures.

**APPROACH**

As part of a general analysis for reducing energy consumption for lighting in commercial facilities, BFRL will examine options related to testing and measurement of lighting fixture and system performance at the component and building operation level. The effort will focus on ways of determining lighting efficiency for both new and retrofit applications.

In FY 1991, BFRL will peform five tasks:

1. Identify and evaluate industry, Federal, state and local standards and regulations for efficiency labeling of lighting fixtures, systems, and controls to determine requirements and criteria for test and measurement procedures for individual components and building interaction. Determine areas of overlap and inconsistency between standards, regulations, and proposed legislation. Collect and review existing technical research literature as appropriate for evaluating existing standards, regulations, and test procedures.

2. Identify and analyze existing lighting fixture and total system test and measurement procedures for determining efficiency performance. Evaluate industry and association testing guidelines and procedures. Develop criteria for evaluating lighting efficiency and performance, including; energy usage, energy cost, and lighting efficiency. Other subsidiary issues are the effect of fixture and system performance on heating and cooling, illumination quality, glare, color, combinations of equipment, and user and environmental effects, as they relate to lighting system and component efficiency and performance.

3. Determine ballast efficiency, fixture efficiency, and lamp efficiency and combine mathematically to determine lighting system efficiency. Determine likely energy usage and cost for equivalent light levels. The approach also includes an assessment of test and measurement procedures to evaluate control and system performance within a building.

4. Develop draft test procedures based on review of the existing test procedures, regulations, and guidelines, and on determination of unit of analysis. Prepare proposed procedures for individual components, particularly lamps, ballasts, fixtures, controls and for systems comprised of these components. Develop method for determining component performance characteristics to enable system performance to be calculated for different component combinations, taking into consideration interactive effects. Provide guidelines for selecting appropriate procedures for intended use.

5. Conduct evaluation of proposed test procedures on three lighting systems in the BFRL lighting test facility. Determine energy usage and cost for equivalent light level for the test cases. Feedback from the testing would be used to improve proposed test procedures as needed. Use results to validate and refined proposed test procedures.

The results of this project will provide testing procedures for lighting systems that acan be used by DOE in their Regulatory Program for Appliances.

**RECENT RESULTS**

New project in 1991.

# BUILDING FIRE PHYSICS

## SURFACE HEAT TRANSFER ALGORITHM

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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop algorithms and associated subroutines that generalize the calculation of radiation and convection heat transfer exchanges between fire, layers, and ceiling/wall/floor surfaces in compartment fires.

**PROBLEM** Heat transfer calculations in existing compartment fire models are limited by their inability to simulate the typically significant spatial heat transfer and temperature distributions on wall/ceiling/floor surfaces. For reliable predictions, this limitation must be removed.

**APPROACH** During FY 1991, BFRL is developing a strategy for defining room geometry and the radiation properties of inside surfaces and upper and lower gas layers. A data structure for dividing and identifying each of the six surfaces of an arbitrary rectangular-parallelopiped room into an arbitrary number of rectangular elements (and a "residual" element) will be performed. A "net radiation-type" analysis and associated subroutine software for calculating heat transfer exchanges between all surface elements, the two gas layers, and a radiating point-source fire of arbitrary location and strength will be performed. BFRL will test the software.

In calculating radiation exchange for the generic room of a facility, a strategy needs to be developed to take account of radiation leaving and entering vents. The radiation calculation methodology will be documented. Algorithms/software for convective heat transfer from the fire plume and from vent flow-driven plumes to ceiling/wall surface elements will be developed and documented. The resulting products will be used to improve existing multi-room compartment fire models.

**RECENT RESULTS** New project in FY 1991.

## FIELD MODELING FOR BUILDING FIRE PHYSICS

*Principal Investigator:* John Klote
Fire Science and Engineering Division
301.975.6879

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop field modeling capability and demonstration application of simulating transport of fire gases including detailed fluid dynamic and heat transfer effects.

**PROBLEM** Current zone fire models are limited in their simulation of fluid flow and heat transfer. For many applications (sprinkler activation, complex geometries, atrium smoke control, etc.) a higher level of detail will result in significant advancements.

**APPROACH** The commercial field modeling software, FLOW3D, has been acquired. FLOW3D is a commercial packaged computer model to simulate fluid dynamics and heat transfer using a finite difference approach. A compartment fire will be selected for which we have experimental data and which will exercise many of the feature of the field model. The fire will be modeled by FLOW3D with increasing levels of complexity. The results of the model will be graphed using post processing software. A report will be written discussing field modeling and comparing it with zone modeling and experiments.

**RECENT RESULTS** New project in FY 1991.

## COMPARTMENT FIRE MODEL TO SIMULATE THE EFFECTS OF ROOF VENTS, SPRINKLERS, AND THEIR INTERACTIONS

*Principal Investigator:* Leonard Y. Cooper
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301.975.6880

*Sponsor:* American Architectural Manufacturers Association Research Foundation

**OBJECTIVE** To develop a computer fire model for engineering analysis of roof vents, sprinklers and their interactions during fire-generated environments.

**PROBLEM** There are numerous questions about the interaction of sprinklers and roof vents and few answers or data to base decisions. BFRL developed the user-friendly computer code LAVENT (Link Actuated VENTs) and its comprehensive User Guide (NISTIR 89-4122) in FY 1989. LAVENT does not include the effect of sprinkler operation on the fire environment. The effect of sprinkler operation must be considered to allow the fire model simulation to extend beyond the time of first sprinkler actuation.

**APPROACH** During FY 1991, BFRL is developing a model to predict the effects of various vent deployment and actuation schemes within the sprinkler-operating environment. The analysis and the corresponding computer code will be capable of simulating smoke layer growth in a curtained area of a building space. The action of fusible-link-actuated ceiling vents on the fire environment will be taken into account. The model will consider first sprinkler actuation by a fused link and the effect of subsequent sprinkler-spray cooling of the accumulating ceiling-level smoke layer on subsequent sprinkler link responses. The fire is assumed to be specified.

This work will lead to an improved version of LAVENT which will incorporate a modular subroutine for simulating the interaction of an isolated sprinkler and an upper layer of arbitrary temperature and thickness. A preliminary submodel for the sprinkler/layer interaction phenomenon was completed in FY 1990. Combining a computerized version of the final submodel and the improved LAVENT will lead to the fire model computer code LAVENTS (Link-Actuated VENTs and Sprinklers). The LAVENTS model will be used to study the interaction of vents and sprinklers, leading to better codes and practices.

**RECENT RESULTS**

Cooper, L. Y., "Estimating the Environment and the Response of Sprinkler Links in Compartment Fires with Draft Curtains and Fusible Link-Actuated Ceiling Vents-Theory," *Fire Safety Journal* 16, pp. 137–163, 1990.

Davis, W. D. and Cooper, L. Y., "A Computer Model for Estimating the Response of Sprinkler Links to Compartment Fires with Draft Curtains and Fusible-Link-Actuated Ceiling Vents," *Fire Technology*, 1991.

Heskestad, G., *Sprinkler/Hot Layer Interaction*, FMRC Report to NIST under Grant 60NANBOD1006, 1990.

## FIRE AND SMOKE SPREAD IN SHIPS – CEILING/FLOOR VENTS

*Principal Investigator:* Leonard Y. Cooper
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*Sponsor:* Naval Research Laboratory
Naval Technology Center for Safety and Survivability

**OBJECTIVE**

To develop a procedure, for use in fire model computer codes for Naval ships, to model smoke flow through horizontal vents in multiroom zones.

**PROBLEM**

Compartments in ships are often connected by openings in the floor/ceiling which have a significant impact on fires in those compartments. Airflow through horizontal openings are driven by buoyancy-generated instabilities. These flows across horizontal vents are extremely difficult to simulate mathematically; they have been unsolved for multiroom compartment fire models.

**APPROACH**

During 1991, BFRL will develop an algorithm and computer subroutine to calculate the characteristics of the flow across a horizontal vent which connects two adjacent spaces of a multiroom facility. The two spaces joined by the horizontal vent can be two inside rooms of a multiroom facility or one inside room and the outside ambient environment local to the vent. The description of the flow through the vent is determined by combining considerations of 1) the unidirectional-type of flow driven by a cross-vent pressure difference and, when appropriate, 2) the exchange-type of flow induced when the fluid configuration across the vent is unstable, i.e., when a relatively cool, dense gas in the upper space overlays a less dense gas in the lower space. Characteristics of the geometry and the instantaneous environments of the two spaces are assumed to be known and specified as inputs.

The outputs calculated by the algorithm/subroutine are the rates and the properties of the vent flow at the elevation of the vent as it enters the top space from the bottom space and/or as it enters the bottom space from the top space. Rates of mass, enthalpy, and products of combustion extracted by the vent flows from upper and lower layers of inside room environments and from outside ambient spaces are determined explicitly. The algorithm/subroutine is called VENTCF. The computer subroutine is written in FORTRAN 77. The subroutine is modular, and is suitable for general use in two-layer, multiroom, zone-type fire model computer codes. It has been tested over a wide range of input variables and these tests are described in the first report listed under results.

The results of this project will provide the basis for improving compartment fire modeling capabilities and are expected to provide the U.S. Navy with an advanced design tool.

**RECENT RESULTS** Cooper, L. Y., *An Algorithm and Associated Computer Subroutine For Calculating Flow Through a Horizontal Ceiling/Floor Vent in a Zone-Type Compartment Fire Model*, NISTIR 4402, October 1990.

## FIRE EVACUATION BY ELEVATORS

*Principal Investigator:* John Klote
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*Sponsor:* General Services Administration
Public Buildings Service
Office of Real Property Management and Safety

**OBJECTIVE** To study the feasibility of using elevators for general fire evacuation.

**PROBLEM** Fire evacuation by stairs is often time consuming and not appropriate for people with physical disabilities. The adaptation of elevators for general fire evacuation is a potential solution to these problems.

**APPROACH** During FY 1991, BFRL will develop conceptual systems for elevator evacuation based on information from the literature and contacts with the elevator industry. Practical concerns such as elevator door jamming, reliability of power, exposure to water, etc., with these conceptual systems will be evaluated. Methods of evacuation analysis and smoke protection analysis for these elevator evacuation systems will be developed. Human behavioral response to these systems will be studied. The feedback from the human behavior study is essential to assure that the earlier efforts are going in an appropriate direction.

**RECENT RESULTS** New project in FY 1991.

## EVALUATION OF STAGING AREAS FOR THE HANDICAPPED

*Principal Investigator:* John Klote
Fire Science and Engineering Division
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*Sponsor:* General Services Administration
Public Buildings Service
Office of Real Property Management and Safety

**OBJECTIVE** To develop methods for evaluating the fire safety of the staging area for the handicapped during building fires, and applying these methods to the staging areas in six GSA buildings.

**PROBLEM** The fire safety of the handicapped in multi-story buildings is of considerable concern. Designated staging areas is one approach that has gained considerable attention for providing fire safety. A method for smoke transport in buildings has been developed and is applicable to sprinkled fires. This method is based on an idealized building network consisting of floors with negligible leakage, shafts, and staging areas for the handicapped.

**APPROACH** During FY 1991, BFRL will develop an analysis of a fire in an office building incorporating stack effect and wind. This analysis is selected as a worse case for design calculations. The method will include sprinkled and unsprinkled fires. In addition to analytical equations of smoke transport, the possibility of using a computer fire model is being investigated. The results from this project are expected to improve safety for handicapped individuals occupying public buildings.

**RECENT RESULTS** New project in FY 1991.

# FIRE DYNAMICS

## WALL FIRE SPREAD

*Principal Investigator:* Henri E. Mitler
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301.975.6886

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop a method for predicting the rate and extent of fire spread on interior surfaces in a room using the fire properties of the materials involved.

**PROBLEM** BFRL's building-fire model (CFAST) lacks the ability to model wall fires. It is important to effectively simulate a growing fire in an enclosure because wall fires lead to rapid flashover, and therefore represent major threats to the building occupants.

**APPROACH** During 1989 and 1990, BFRL developed the model/program SPREAD which predicts upward fire spread on thick walls. During 1991, this model is being generalized to include lateral spread and the effect of burnout of thin walls; also, the effects on burning (pyrolysis) and spread rates of burning and combustion in a hot, oxygen-vitiated atmosphere (such as exists under the ceiling of the burning room) are being examined both theoretically and experimentally. This will permit extension of the program to a two-layer environment. Finally, a new technique for calculating the pyrolysis rate for arbitrary materials is being validated and will be incorporated into SPREAD. In 1992, a general model including char-forming materials and composites burning in different configurations including flat walls, corners and ceilings will be completed and experimentally verified.

BFRL's model provides manufacturers, architects, and modelers with the ability to predict the rate of fire development on vertical surfaces and to assess the fire hazard of interior finish materials from bench-scale measurements and the use of validated computer models, rather than from time-consuming full-scale tests.

**RECENT RESULTS** The results of last year's effort include:

Kulkarni, A. K., Kim, C. I., and Mitler, H. E., "Time dependent local mass loss rate of finite-thickness burning walls," submitted for the 1991 ASME Winter Annual Meeting, Symposium on Fire and Combustion Systems, 1990.

Mitler, H. E., "Predicting the spread rates of fires on vertical surfaces," *23rd (International) Symposium on Combustion;* The Combustion Institute, Pittsburgh, PA, 1990.

Mitler, H. E., "Algorithm for the Mass-Loss Rate of a Burning Wall," *Fire Safety Science—Proceedings of the Second International Symposium* (Eds., C. E. Grant and P. J. Pagni); Hemisphere Publishing Corp., p. 179, 1988.

**GRANTS** Alpert, R. and deRis, J., *Prediction of Fire Dynamics*, Factory Mutual Research Corp., Norwood, MA.

Kulkarni, A., *Upward Flame Spread on a Vertical Wall*, Pennsylvania State University, PA.

Saito, K., *A Study of Fire-Induced Flow Along the Vertical Corner Wall*, University of Kentucky.

## THE USE OF FIRE PROPERTY TESTS FOR PREDICTING MATERIAL PERFORMANCE

*Principal Investigator:* James G. Quintiere
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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop a first order model on the fire energy and product output of room surfaces by using fire property test data.

**PROBLEM** Current fire tests provide relative rankings of performance without accounting for the actual use of the product.

**APPROACH** During FY 1991, BFRL will quantitatively show how data from BFRL's Cone and Lift apparatuses can be used to predict the energy release rate of fire growth on room surfaces. BFRL's fire models will be reviewed to determine the best way to couple in feedback effects. This work will include thermal effects; oxygen depletion will be considered. A single-room fire model will be selected to link with the fire growth model. The coupled room fire growth model will be coded and its results assessed against available data. Probable cases would be run against some of the plastic materials for illustration. The new fire test methods will be designed for the fire code and standards community.

It is expected the results of this project will help develop rational fire hazard assessments and provide appropriate technical information for consideration in the EC 92 harmonization process. Also, this work will help provide a framework for more complete models. A report on the new fire test methods is expected during the fall, 1991.

**RECENT RESULTS** New project in FY 1991.

## FURNITURE FLAMMABILITY

*Principal Investigator:* Henri E. Mitler
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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To develop experimental and theoretical methods for predicting the hazard from burning furniture, especially upholstered furniture.

**PURPOSE** Fires in upholstered furniture are the primary cause of fire fatalities in the U.S. A procedure is needed to assess upholstered furniture flammability.

**APPROACH** During 1991, BFRL will develop a criterion for when flashover will occur under transient conditions, as distinct from the usual assumption of steady state. Flashover is the principal hazard—i.e., the principal determiner of whether mortality will occur—during a fire. BFRL's computer program (Hazard 1) and other room fire model(s) will be exercised to evaluate under what sets of circumstances flashover occurs and whether that is indeed when the hazard from various furniture fires becomes large.

BFRL will determine the dependence of the rate of heat release of each of several furniture items on the ignition mode and determine its dependence on where on the item the igniter is applied, for at least one item. Several ignition sources will be used to ignite a set of chairs with different fabric/padding combinations, in BFRL's furniture calorimeter. The heat release rate and CO generation rate will be inserted into Hazard 1 and escape time will be assessed for a few representative residential scenarios. Two or three sets of upholstered chairs will be ignited with burner, at different points: on the seat, at the side, at the back, and underneath; the spread rate and rate of heat release will be found for each, and compared.

The Dietenberger furniture-burn model will be assessed and its theoretical limits of validity examined. It also will be exercised, and its results compared with measurements.

An understanding of the way furniture performs when subjected to various ignition sources, and its subsequent burning behavior, will enable manufacturers, standards organizations, and/or regulators to assess the hazard from that furniture in various occupancies.

**RECENT RESULTS**

Quintiere, J., *Furniture Flammability—An Investigation of the California Technical Bulletin 133 Test, Part I. Measuring the Hazards of Furniture Fires,* NISTIR 4360, 1990.

Ohlemiller, T. J. and Villa, K., *Furniture Flammability—An Investigation of the California Technical Bulletin 133 Test, Part II. Characterization of Ignition Source and Comparable Gas Burner,* NISTIR 4348, 1990.

Parker, W. J., Tu, K-M., Nurbakhsh, S., and Damant, G. H., *Furniture Flammability—An Investigation of the California Technical Bulletin 133 Test, Part III. Full-Scale Chair Burns*, NISTIR 4375, 1990.

## IGNITION BY CIGARETTES

***Principal Investigator:*** Henri E. Mitler
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***Sponsor:*** Consumer Product Safety Commission

**OBJECTIVE**

To develop a mathematical (computer) model of a smoldering cigarette lying on an item of upholstered furniture for the cases of the item heating up and ignites and the case when it does not ignite.

**PROBLEM**

Cigarette ignition of soft furnishings is the leading single cause of fire fatalities in the United States. In order to design a cigarette which has a lower propensity to ignite upholstered furnishings than the current version, the ignition mechanisms must be quantitatively understood. A model which incorporates the proper physics and chemistry involved can help lead manufacturers to design cigarettes which will have a lower propensity to ignite furnishings.

**APPROACH** This work builds on past years' model development efforts. Each model consists of a set of nonlinear partial differential equations which describe the dynamics of the several processes taking place: heat transfer by convection and radiation, pyrolysis, and convective mass transfer (gas flows). The cigarette and substrate models developed in 1987 are being extended in several ways: the substrate model will be extended to include noninert materials; perhaps, also, two-layer substrates (fabric over padding). The reactivity of the substrate will be handled in a simplified way—local pyrolysis will be taken to be a function of temperature (using an Arrhenius relationship) and an ignition temperature will be assumed. The cigarette model will be improved by including several aspects of the physics which were omitted in the former model. In particular, the inclusion of the gas continuity equation and the ideal gas law are important; radiation loss from the surface also will be included. Because of the complexity of the task and the relatively short time available, the problem is being decoupled. That is, two models are being developed: one for the substrate, and another for the smoldering cigarette; their interaction will be handled through boundary conditions and alternate use of the two models.

**RECENT RESULTS**

Gann, R. G., Harris, R. H. Jr., Krasny, J. F., Levine, R. S., Mitler, H. E., and Ohlemiller, T. J. (1988), "Cigarette Ignition of Soft Furnishings," *Fire Safety Science—Proceedings of the Second International Symposium* (Eds., C. E. Grant and P. J. Pagni); Hemisphere Publishing Corp., p. 77, 1989.

Mitler, H. E., and Davis, W. D., "Computer Model of a Smoldering Cigarette," *Annual Conference on Fire Research*, National Bureau of Standards, Gaithersburg, MD, November 1987.

Mitler, H. E., "Modeling Ignition," Section 5 in *The Effect of Cigarette Characteristics on the Ignition of Soft Furnishings*, by Gann, Harris, Krasny, Levine, Mitler, and Ohlemiller, Natl. Bur. Stand. (U.S.), Tech. Note 1241, 1988.

## FLAMMABILITY OF PIPES

***Principal Investigator:*** Henri Mitler
Fire Science and Engineering Division
301.975.6886

***Sponsor:*** U.S. Coast Guard
Marine Safety Laboratory
Fire and Safety Research Division

**OBJECTIVE** To develop a method for assessing the flammability of plastic pipes used on Coast Guard ships.

**PROBLEM** As plastic pipes are substituted for metal ones on ships, the possibility of their adding to the hazard of an unwanted fire increases. It is therefore important, for planning purposes, to know in advance the potential hazard of the materials.

**APPROACH** Some of the important flammability characteristics of a material, such as the rate of lateral spread of a fire, can be determined by using the IMO (International Maritime Organization) apparatus, which is almost identical to the LIFT (Lateral

Ignition and Flamespread Test) apparatus, used at BFRL. These tests use flat samples of material. During 1991, BFRL will determine the flaming behavior of the materials in a cylindrical configuration. The IMO test protocol will be modified to accept the different sample shape and permit meaningful analysis of the results.

**RECENT RESULTS** New project in FY 1991.

## FIRE HAZARDS STUDY OF WIRE AND CABLE PRODUCTS

*Principal Investigator:* Richard W. Bukowski
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*Sponsor:* National Electrical Manufacturers Association

**OBJECTIVE** To develop evaluation methods of the fire hazards of wire and cable products based on in-service product use.

**PROBLEM** The current wire and cable products regulation is based largely on tests which evaluate performance by directly exposing the product to a fire. In normal application, nearly all wire and cable is enclosed within or behind materials with significant fire resistance. The wire industry request test data based on the product's normal environment.

**APPROACH** BFRL will perform a literature review to establish the current state-of-the-art of testing of wire and cable products. Expanding on recent BFRL work in fire hazard and fire risk assessment, an analytical model will be developed to evaluate the desired quantification of the product's hazard. This process will identify the data and knowledge needed to complete the analysis. It is expected that the findings will result in a more realistic product regulation and a means to quantify the benefits of improving the product's fire performance.

**RECENT RESULTS** New project in FY 1991.

# COMBUSTION AND FLAMMABILITY

## BURNING RATE

*Principal Investigator:* Takashi Kashiwagi
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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To understand the physical and chemical gasification processes of various polymers, to develop theoretical models to predict the gasification rates of polymers exposed to fire conditions, to understand energy feedback mechanisms of pool fires, and to develop models to predict energy feedback rates from a pool flame to the fuel surface.

**PROBLEM** To accurately predict the rate of fire growth and smoke generation during a fire of polymeric materials, a quantitative understanding of the physical characteristics and the physical and chemical processes which impact the burning rate is needed. Current fire growth models prescribe the magnitude and the increase of the heat release rate over time in a fire. A better understanding of the rates of material gasification, heat release and heat feedback to the material surface is needed to model material burning rates.

**APPROACH** During FY 1991, BFRL is conducting experiments and developing models to accurately predict horizontal burning rates of polymers. Research is underway on 1) determining the relationship between the physical properties of a polymer and its rate of gasification and 2) determining heat feedback from a fire to the surface of the burning material.

The polymer gasification study is looking at the physical and chemical processes which affect polymer gasification. An experimental apparatus for studying the transient gasification of materials exposed to radiant heating in a nitrogen atmosphere is being constructed. A number of parameters will be measured as a function of incoming heat flux. These include the rate of polymer gasification, temperatures inside and on the surface of the polymer, bubble/char characteristics of various thermoplastics. An analytical surface-absorption model for the one-dimensional gasification of a noncharring thermoplastic material subjected to a specified, time-dependent external radiant heat flux has been developed. The model assumes a well-defined vaporization temperature and heat of gasification.

The heat feedback program is conducting a detailed study of the heat transfer processes which occur in pool flames. Pool burning experiments have been conducted in a 30 cm diameter water-cooled pool burning apparatus which consists of four concentric rings. Each ring is fed independently to monitor burning rates and to maintain the liquid level close to the rim. Total heat feedback as a function distance from the center of the pool is determined for a number of fuels which yield flames with highly varying amounts of radiative heat losses and combustion efficiencies.

A global mass burning rate model based on a mean beam length radiative transfer approximation was developed. A cylindrical flame shape is assumed. Flame temperatures are calculated taking into account radiative losses and combustion efficiency. Gray body absorption-emission coefficients are calculated from a mean beam length approximation and data on the fraction of idealized combustion

energy radiated to flame surroundings. Predictions of burning rates are accurate to within a factor of two for luminous flames, but the calculated gray body absorption-emission coefficients are inconsistent with those experimentally determined.

The results of this work will produce a fundamental advancement for fire models providing knowledge to predict the rate of burning objects.

**RECENT RESULTS**

Hamins, A., Klassen, M., Gore, J., and Kashiwagi, T., "Single Location Estimates of Radiative Loss Fractions in Pool Fires," submitted to *Combustion and Flame.*

Steckler, K. D., Kashiwagi, T., Baum, H. R., and Kanemaru, K., "Analytical Model for Transient Gasification of Noncharring Thermoplastic Materials," to be presented at the *Third International Symposium on Fire Safety Science,* Edinburgh, Scotland, July 1991.

Kashiwagi, T., Omori, A., and Nanbu, H., "Effects of Melt Viscosity and Thermal Stability on Polymer Gasification," *Combustion and Flame*, 81, pp. 188–201, 1990.

## TURBULENT COMBUSTION SIMULATION

*Principal Investigator:* Howard R. Baum
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*Sponsors:* Department of Interior
Minerals Management Service, Technology Assessment and Research Branch, and National Institute of Standards and Technology

**OBJECTIVE**

To develop a fundamental understanding of the mechanisms which control gas phase combustion processes in fires and a predictive capability to allow the evolution of these processes to be calculated from basic principles.

**PROBLEM**

A theoretical and computational approach is needed to study the transport, mixing, diffusion, and reaction processes in an enclosure fire context. Each process is considered in detail at the appropriate level of description. Since these phenomena occur at widely different length and time scales, it is needed to provide a set of overlapping analyses in frames of reference which will permit the phenomena to be coupled together.

The existing three dimensional inviscid flow model now permits the direction of gravity to be oriented arbitrarily, permitting fire driven flows in inclined rooms and corridors to be studied. In addition, a new two dimensional high resolution Navier Stokes code with the same capability were developed. These codes were applied to study the effects of this inclination on gravity currents in corridors generated by fires. This "trench effect" was a central issue in the disastrous Kings Cross underground fire in London in 1987.

**APPROACH**

In FY 1991, BFRL will develop a vortex dynamics simulation of the wind blown smoke plume in collaboration with Professor A. Ghoniem of MIT. It will describe the descent of a cool particulate plume and its dispersal over a ground plane. The concept of the Pseudo-Mixture fraction, an entity developed as part of the study of small scale combustion processes in fires, will be rederived in a very general context in collaboration with Professor J. Gore of the University of Maryland. In

its new, more general form, it can be used in the two-dimensional Navier-Stokes simulation model after suitable modifications to that code.

The result of this research will be an analysis and computer codes which collectively integrate fluid flow, heat transfer, and combustion phenomena in prototypical fire scenarios. These results will lead to advanced predictive capabilities.

**RECENT RESULTS**

Rehm, R. G., Baum, H. R., Lozier, D. W., Tang, H. C., and Sims, J., "Buoyant Convection in an Inclined Enclosure," to be presented at the Third International Symposium on Fire Safety Science, Edinburgh, Scotland, July 1991.

Baum, H. R., Rehm, R. G., Gore, J. P., "Transient Combustion in a Turbulent Eddy," to appear in the Proceedings of the Twenty-third Symposium (International) on Combustion, 1991.

Rehm, R. G., Baum, H. R., Lozier, D. W., and Aaronson, J. J., "Diffusion–Controlled Reaction in a Vortex Field," *Combustion Science and Technology, 66,* p. 293, 1989.

## RADIATIVE IGNITION AND SUBSEQUENT FLAME SPREADING IN MICROGRAVITY ENVIRONMENT

*Principal Investigator:* Takashi Kashiwagi
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*Sponsor:* National Aeronautics and Space Administration
Microgravity Science Program,
NASA Lewis Research Center

**OBJECTIVE**

To develop a theoretical model for predicting ignition and subsequent flame spreading over a thin cellulosic material in a microgravity environment using material characteristics determined in normal gravity environment.

**PROBLEM**

There is always a buoyancy induced flow in any combustion study due to high temperature gases by combustion. Since the induced flow is characterized by an elliptic nature, its influence on combustion is extremely complex and hinders severely to understand the combustion mechanism and the calculation of theoretical problems. The study in microgravity allows us to be able to conduct experiments and make theoretical models without influence of the buoyancy induced flow.

**APPROACH**

A two-dimensional axisymmetric time-dependent ignition model in a quiescent microgravity condition has been developed. Its gas phase model is based on irrotational flow mainly controlled by gas expansion and mass addition from degrading condensed fuel with one-step oxidative reaction with energy and species equations. Its condensed phase model is based on the thermally thin cellulosic sheet with three global degradation reactions, pyrosis reaction and oxidative degradation of the sheet to generate char and gaseous products, and oxidative char degradation. The calculated results show that the event of ignition occurs roughly 1 cm above the surface depending on kinetic constants of the gas phase oxidative reaction. An umbrella shape flame appears but this flame cannot be sustained to flame spread with typical values of kinetic constants of gas phase and condensed phase reactions due to lack of enough supply of oxygen and fuel

species. Effects of gas phase oxygen concentration and the fuel fraction in the degradation products on ignition are being studied. Determination of kinetic on ignition are being studied. Determination of kinetic constants of the three degradation reactions are nearly completed using TGA analysis with multiple heating rates and oxygen concentrations and by continuous evolved gas analysis of CO, $CO_2$, $H_2O$, and $O_2$.

The understanding of these phenomena will be applied to fire safety in a spacecraft and the space station.

**RECENT RESULTS**

Kushida, G., Baum, H. R., and Kashiwagi, T., "Heat and Mass Transport From Thermally Degrading Thin Cellulosic Material in a Microgravity Environment," submitted to *JEME/ASME* Meeting, March 1991.

Kushida, K., Baum, H. R., and Kashiwagi, T., "Ignition of Thin Cellulosic Material in a Quiescent Microgravity Environment," presented at *1990 Fall Technical Meeting,* Eastern Section of the Combustion Institute, December 1990.

## MATERIAL FLAMMABILITY TEST ASSESSMENT

*Principal Investigator:* Thomas Ohlemiller
Fire Science and Engineering Division
301.975.6481

*Sponsor:* National Aeronautics and Space Administration
NASA Lewis Research Center

**OBJECTIVE**

To assess the current NASA flammability test method against tests used at NIST for measuring the elements of material flammability and to assess the feasibility of estimating microgravity flammability from normal gravity testing.

**PROBLEM**

The impending Space Station, with its projected occupancy time of 20 to 30 years, poses a greater potential fire safety problem than any previous spacecraft. The existing fire safety procedures, including the screening test for flammability of spacecraft interior materials, the subject of the current study, are being closely scrutinized for their ability to meet this greater challenge.

**APPROACH**

During FY 1991, BFRL is testing five materials of interest to NASA for spacecraft interior usage using a modified NASA flammability assessment method (NHB 8060.1B) in ambient air and using the ignition and rate of heat release and lateral flame spread tests developed at NIST. The NASA test is based on the upward flame spread on a small sample of a material when subjected to a small flaming ignition source for a fixed duration (approx. 25 s). The text has been modified to permit radiative preheating of the sample and determination of the minimum preheat condition necessary for upward flame spread. The BFRL tests all subject a material to a range of incident radiant heat fluxes comparable to those expected from the burning of other objects near the object of interest. Under these circumstances, given a sufficient external flux (which varies with the nature of the material), all of the materials ignite, exhibit a significant rate of heat release and lateral flame spread rate. In the modified NASA tests, the materials exhibit widely varying responses to the preheating as revealed by the extent of upward flame spread. An attempt is being made to predict the NASA test behavior on the basis of the NIST test results.

The second objective is being addressed by studying available models of the elements of flammability and an examination of the role that gravity plays in these processes.

A report on the results to date is in preparation.

The results from this research are expected to provide NASA with improved means to assess the flammability hazards of marginal materials.

**RECENT RESULTS** New project in FY 1991.

## LOW FLAMMABILITY COMPOSITES

*Principal Investigator:* James E. Brown
Fire Science and Engineering Division
301.975.6483

*Sponsor:* Department of the Navy
David Taylor Research Center

**OBJECTIVE** To develop a bench-scale method for evaluating the fire performance properties of fiber-reinforced composites to assist the Navy select composite materials for use on ships.

**PROBLEM** The Navy has many proposed applications for using composites on ships. These applications would replace metals and result in economic and tactical military advantages. Because composites contain organic resins, a potential hazard of fire may be increased. Information on the fire performance of the composites in a broad range of conditions must be known to Navy designers to make intelligent decisions. The composition of composites consists of a noncombustible and potentially combustible components and thus makes predicting the fire performance unique. Such information is not currently available.

The BFRL Cone Calorimeter and flame spread apparatuses have been established as the most promising methods for characterizing the flammability of materials. However, recent research indicates that effects of sample orientation, thickness, and the ratio of peripheral edge length to exposed surface area may limit the direct application of these small-scale laboratory results to full-scale fire behavior. Further development of these methods and use of other techniques and hazard analysis will be required to predict full-scale fire performance.

**APPROACH** The first phase of a study to quantify the heat feedback from the flame to the burning surface was completed. Based on a energy balance concept for mass loss rate, the flame heat flux to the surface is ascertained from the difference in the inferred mass loss rates where the external flux approaches zero.

Composite materials have the potential for a form of nonideal behavior which is termed an "edge effect." Pyrolysis gases generated between the fiber plies during surface heating of a composite will seek the path of least resistance in escaping from the composite. This path may lead to the edge of the sample rather than the face if the plies have some tendency to delaminate and if the outer plies are clogged by char from the binder resin. This effect is more likely to affect the

small samples used in Cone Calorimeter and LIFT tests than it is to affect full scale wall panels; the path to an edge is likely to be much longer in the latter case.

A modified sample holder is being used to study the effect of edges. To prevent the leakage path to sample edges, the sample size is increased by 25 mm around the periphery; this added edge material is kept cool and tightly clamped during exposure of the normal area of sample face to a radiant heat flux. Such a holder was used to examine rate of heat release, burning rates and thermal sensitivity indices of composites in the Cone Calorimeter. Preliminary analyses of the results indicate that the conventional Cone results represent the worst case scenario. The heat-sinking effect of the unburned surrounding material is to be quantified with respect to the materials burning rate.

An analogous holder was also built for the LIFT apparatus to allow assessment of the impact of edge effects on lateral flame spread behavior. This study is ongoing; preliminary results indicate that the magnitude of such effects is strongly dependent on the nature of the binder resin and, most likely, the nature of the fiber weave in the composite. Heat release rate and flame spread rate are being viewed with the idea of input to a model to predict fire performance of composites.

The understanding of composite flammability will allow more applications of these materials.

**RECENT RESULTS**

Brown, J. E., "Heat Release and Flammability of Composites," Chapter in *The Cone Calorimeter and Heat Release of Materials*, Grayson, S. J. and Babrauskas, V., Eds., Interscience, in press.

## FLAME RETARDANT STUDY

*Principal Investigator:* Takashi Kashiwagi
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301.975.6699

*Sponsor:* General Electric Corporation
Chemical Research Center

**OBJECTIVE**

To establish the effects of polymer structure and certain additives on flammability characteristics of GE's engineering thermoplastics to develop more flame retarded polymers.

**PROBLEM**

Flame retarded polymers are developed by a try-and-error approach. More systematic study and studies to understand how flame retardants reduce heat release rate and formation of particulates are needed to develop or discover better flame retarded polymers. Another important study is the measurement of flammability properties of flame retarded polymers. The traditional pass/fail measurement does not provide useful information about the effectiveness of flame retardation. More material performance oriented flammability measurements are needed.

**APPROACH**

During FY 1991, flammability properties, ignition, flame spread rate, heat release rate, CO and soot yields, and smoke extinction are being measured for various polycarbonates with and without additives. The effects of external radiant flux on

the flammability properties of these sample will be determined using BFRL's Cone Calorimeter and LIFT devices. Since these samples intumesce during burning, a course wire screen will be used to retain the sample surface at the original location. However, it is not clear that flammability properties obtained under this configuration represent material property characteristics which can be used for fire growth models, although the measured properties are highly reproducible. To examine the effects of the sample mounting method on flammability properties, additional sample mountings, without the wire screen and without a metal sample container will be performed. The tests will provide data to determine which additive is the most effective for polycarbonates. Several large scale burning experiments with commercially available polycarbonates and polyimides are planned using the furniture calorimeter and the data will be compared with the calculated results using material flammability properties determined previously. A preliminary study to understand the flame retardant mechanism of one selected additive in polycarbonate will start during the fall of 1991.

The results of this work will improve understanding of the flame retardant mechanism of polycarbonate and will provide guidelines to increase its flame retardation.

**RECENT RESULTS**

The measurement of flammability properties of commercial polycarbonates, polyimides and PPO samples were completed.

# FIRE SAFETY ENGINEERING

## LIVE FIRE TESTING

*Principal Investigator:* Robert S. Levine
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*Sponsor:* Office of Secretary of Defense
Office of Live Fire Testing

**OBJECTIVE** To support the Office of Secretary of Defense with independent analysis of possible effects of fire resulting from live military tests in submarines.

**PROBLEM** Congress has requested an independent analysis of Military Live Fire (real munitions and real systems) tests, and the planning for such tests.

**APPROACH** During FY 1991, BFRL is addressing fire hazards in new Navy ship designs, especially the "Sea Wolf" sea control submarine. Fires are apt to start as collateral damage from shock e.g., mines, depth charges, failure or misuse of on-board equipment. Analysis of previous incidents on naval craft, especially submarines are being studied. One problem is the submarines atmospheric recovery systems ability to contend with on-board fire. Also included are the effects of fire on the equipment and structure, personnel burns, the effects of toxic fire gases, and effects on the operability of the equipment.

This work is being performed in conjunction with personnel at the Institute for Defense Analysis, also contractors to the sponsor.

**RECENT RESULTS** Briefings to sponsor.

## EFFECTS OF FIRE SUPPRESSANTS ON SAFETY-RELATED EQUIPMENT IN NUCLEAR POWER PLANTS

*Principal Investigator:* Robert S. Levine
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*Sponsor:* Nuclear Regulatory Commission,
Office of Nuclear Regulatory Research

**OBJECTIVE** To furnish data and analysis to NRC's study, performed at Sandia National Laboratory, of inadvertent operation of in-place fire extinguishing systems in U.S. nuclear power plants.

**PROBLEM** Over 100 incidents of inadvertent operation of in-place fire extinguishing systems in U.S. nuclear power plants were reported over the last 10 years. Almost no two are alike. About 40 incidents concerned NRC because of safety circuits and equipment. Since the data are sparse, it is difficult to assign probabilities in the Sandia reliability study.

**APPROACH** During FY 1991, BFRL is studying data on inadvertent actuation of fire fighting systems, and the effects of leaks or other contact of water with equipment. Some of the populations of Navy Safety Center data resemble the population of Nuclear Power Plant data and are being studied in categories selected in concert with staff at the Sandia National Laboratory. The project examines Department of Navy experiences with their large variety of operating systems onboard ships and shore facilities to gain insight into the effects that might occur. A final report of the project will be published in the fall 1991.

**RECENT RESULTS** New project 1991.

## NAVY FIREFIGHTER TRAINERS

*Principal Investigator:* Robert S. Levine
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*Sponsor:* Department of the Navy
Navy Training Systems Center

**OBJECTIVE** To develop fire safety procedures and prediction computer programs for U.S. Navy firefighter trainers.

**PROBLEM** Skilled firefighting is vital to the survivability of Navy vessels. Under current conditions, a seaman receives hands-on training approximately once in a 3-year hitch. The Navy is developing a series of realistic trainers and will install thirty assorted trainers at various Naval Stations within the United States. These trainers use propane gas as fuel; the fire is controlled by valves which are controlled by microprocessors that react according to data from sensors. The sensors are affected by the adequacy of the trainees in applying agent to the fire. The trainees require safety assurance and reliability for the NAVY.

**APPROACH** During FY 1991, BFRL is performing an assessment of a recruit trainer at the Great Lakes Naval Training Center and an aircraft carrier deck trainer at Treasure Island Naval Station will be performed. BFRL is collecting and analyzing heat flux, temperature, gas composition, and other data from the operating prototype trainers. The findings provide the Navy Training Systems Center with recommendations about the safety of the training equipment. BFRL also is providing technical support in related areas such as corrosion, durability of cement, analysis of gas for minor species such as PAH's, etc.

This program is in its fourth year. Data exist for all the planned trainer types, but there are still problems, such as furnishing data permit for local Air Pollution personnel.

**RECENT RESULTS** Levine, R. S. and Rinkinen, W., *Fire Tests of the Prototype 19F3 Navy Firefighter Trainers*, Report of Test FR 3979, NIST, September 1989.

Levine, R. S. and Greenaugh, K., *Exhaust Gas Analysis for Harmful Species: 19F1A Fire Fighting Trainer at Mayport, Florida*, NISTIR 4318, May 1990.

## BOARD AND CARE HOME FIRE SAFETY ASSESSMENT

*Principal Investigator:* Harold E. Nelson
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*Sponsors:* Department of Health and Human Services
Social Security Administration and
Office of Human Services
Administration on Aging
Administration on Developmental Disabilities and
Health Care Financing Administration and
National Institute of Mental Health and
Department of Education and
National Institute on Disabilities and Rehabilitation Research

**OBJECTIVE** To assess the impact of the publication of Chapter 21 of the Life Safety Code (and related Fire Safety Evaluation Systems), determine the resultant level of fire safety, and identify short comings.

**PROBLEM** Needed is a technical basis for evaluating Chapter 21 of the Life Safety Code for the purpose of sound, cost effective, mission compatible fire safety. Also needed is a procedure to provide this knowledge to the Departments of Health and Human Services and Education to make a rational plan of action related to fire safety in board and care homes. The several standards developing organizations publishing code impacting on board and care homes lack this knowledge.

**APPROACH** During FY 1991, BFRL will perform four tasks:

1. Determine the status of adopting newer publications (e.g., Chapter 21) approaches, and the problems and results of such action.

2. Develop technical guides to assist in successful adoption of approaches from Task 1 and optimize the resulting safety.

3. Improve BFRL's model EXITT to better predict the expected emergency evacuation of a group of individuals with mixed capabilities.

4. Perform the analytical analysis of fire incidents (real if possible, simulated if not) to aid in the evaluation of the import of individual features involved in the fire safety design of board and care homes.

Tasks 1, 2, and 3 are being performed under a grant to Dr. Bernard Levin at the George Mason University. Task 4 is performed at the BFRL laboratories. A report on this work is expected in the fall 1991 containing the results of the analysis of Chapter 21 and a revised model.

**RECENT RESULTS** New project 1990.

## ENGINEERING METHODS

*Principal Investigator:* Harold E. Nelson
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*Sponsors:* National Institute of Standards and Technology and

General Services Administration
Public Buildings Service
Office of Real Property Management and Safety

**OBJECTIVE** To develop a technically sound, easy to use collection of fire protection engineering equations and models useful for evaluating fire safety of compartmented buildings.

**PROBLEM** Fire protection engineers and similar professionals lack modern analytical methods to perform assessments of fire hazards. Also to deliver this to GSA in the form of a fire hazard assessment system suitable for their professional fire safety staff use.

**APPROACH** During FY 1991, BFRL is expanding its prior work and building on research from others to expand its fire hazard models ASET and DETACT and its collection, FIREFORM. The revised models will include the response of sprinklers and detectors, the impact of HVAC equipment, the impact of depletion of oxygen and the generation of carbon monoxide. BFRL will develop user friendly models for implementation to GSA's fire training program. BFRL will train GSA engineers in the use of the final package. A key objective of this work has been completed and presented in the computerized collection FPETOOL. FPETOOL was published with documentation and a users guide.

**RECENT RESULTS**

Nelson, H. E., *FPETOOL—Fire Protection Engineering Tools for Hazard Estimation,* NISTIR 4380, National Institute of Standards and Technology, 1990.

Nelson, H. E., *FPETOOL User's Guide,* NISTIR 4439, National Institute of Standards and Technology, 1990.

Steckler, K. D., *Fire Induced Flows in Corridors—A Review of Efforts to Model Key Features,* NISTIR 89-4050, National Institute of Standards and Technology, 1989.

# SMOKE DYNAMICS

# CARBON MONOXIDE PRODUCTION AND PREDICTION

*Principal Investigator:* William M. Pitts
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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To assess the importance of CO in fire toxicology (i.e., the levels of CO generated) and to provide the scientific background to predict CO in real fires.

**PROBLEM** Studies indicate that roughly two-thirds of fire deaths (approximately 4200 annually in the United States) are the result of elevated carboxyhemoglobin blood levels. Useful models of fire hazards require realistic estimates for CO formation. Despite the importance, an understanding of and predictive capability for CO formation during fires is lacking.

**APPROACH** During FY 1990, BFRL performed an investigation of the effects of vitiation (i.e., dilution of air so that the percentage of oxygen is reduced below 21%) of the air surrounding the fire. The investigation showed that vitiation has a minimal effect on CO production as long as the total amount of oxygen supplied is sufficient for complete combustion.

During FY 1991 research is focused on four components of the overall priority project plan designed to assess whether or not the global equivalence ratio (GER) concept offers a viable approach for the prediction of CO formation in real fire situations. The GER is based on experimental observations in the laboratory which indicate that chemical species in a hood located above a fire burning in ambient or vitiated air can be correlated in terms of the ratio of the gases from fuel and from air. BFRL will assess the validity of extending these findings to a room fire environment and developing algorithms for incorporating the GER into fire models.

Dimensional scaling is being used for the design of a reduced scale enclosure which is a two-fifths model of a model room used for full-scale fire testing. The enclosure is designed so the wall containing the doorway can be replaced with ones having differently sized openings. In this manner the ventilation factor (one of the most important parameters in determining CO formation in fires) for the room can be easily varied. Instrumentation currently includes thermocouples and a variety of NDIR concentration meters. During FY 1991 the enclosure will be constructed and tested and a series of preliminary test completed.

To assess the use of the GER concept for actual fires it is necessary to follow the time variation of the global equivalence ratio in the upper layer of a fire at the same time concentrations of fire gases are being monitored. An instrument based on the complete oxidation of fire gases is currently being designed and tested. It is anticipated that this instrument will be available for use by mid-fall 1991.

A general model based on the GER concept was developed to predict the generation rates of oxygen, fuel, and other products of combustion in rooms containing fires. An algorithm for implementing the model is being prepared. The algorithm will allow predictions of the model to be compared with experiment and will ultimately allow an assessment of the suitability of the GER for predictions of CO formation in fires.

The GER concept requires that the upper layer gases in a fire environment be nonreactive. This aspect of the problem is being addressed by assuming the upper layer behaves as either a perfectly stirred or plug flow reactor and using a full chemical kinetic code to predict the chemical history of the upper layer. Only homogeneous gas phase species are treated. These calculations should allow temperature and concentration ranges where the use of the GER is appropriate to be identified.

**RECENT RESULTS**

Mulholland, G., Janssens, M., Yusa, S., Twilley, W. and Babrauskas, V., "The Effect of Oxygen Concentration on CO and Smoke Produced by Flames," *Third International Symposium on Fire Safety Science*, 1991.

Cooper, L. Y., *A Model for Predicting the Generation Rate and Distribution of Products of Combustion in Two Layer Fire Environments*, NISTIR 90-4403, September 1990.

Pitts, W. M., *Long-Range Plan for a Research Project on Carbon Monoxide Production and Prediction*, NISTIR, 89-4185, May 1989.

**GRANTS**

*"Soot Particle Formation and Destruction in Diffusion Flames,"* Robert J. Santoro, Pennsylvania State University.

*"Radiation from Turbulent Luminous Fires,"* Gerald M. Faeth, University of Michigan.

*"Experimental Studies of the Environment and Heat Transfer in a Room Fire,"* Edward E. Zukoski, California Institute of Technology.

*"Compartment Fire Combustion Dynamics,"* R. J. Roby, Virginia Polytechnic Institute and State University and C. L. Beyler, Fire Science Technologies.

*"Chemical Pathways to the Formation and Emission of the Products of Incomplete Combustion in Diffusion Flames,"* J. H. Miller, George Washington University.

## CHARACTERIZATION OF MIXING AND CHEMISTRY-TURBULENCE INTERACTIONS IN TURBULENT FLOWS

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***Sponsor:*** National Institute of Standards and Technology

**OBJECTIVE**

To interface a CCD-based digital camera which can be used in intensified or unintensified modes with existing lasers and instrumentation to create a powerful, world-class facility for time-resolved, multidimensional (two spatial axes and time) characterization of scalar mixing and reaction behavior in turbulent flows.

**PROBLEM**

Chemistry-turbulent interactions play a dominant role in carbon monoxide and soot formation during turbulent combustion. Characterization of turbulent mixing is necessary for the development of models capable of predicting these complicated chemical processes. A state-of-the art optical diagnostic is being developed for characterizing temporal and spatial mixing behavior in turbulent flow fields.

**APPROACH** Rayleigh light scattering (RLS) is employed as the flow diagnostic. A single light pulse (7 ns) of a frequency doubled Nd/YAG laser is being used as the RLS light source for imaging concentration in a plane. An intensified digital line camera is being used to record RLS and thus real-time concentration fluctuations along a line defined by the beam of a CW argon ion laser. Timing is such that real-time line camera measurements of concentration are recorded just prior to, during, and immediately following the two-dimensional measurements.

**RECENT RESULTS** New project in FY 1991.

## 0.1 μm AEROSOL CONCENTRATION STANDARD

*Principal Investigator:* Nelson Bryner
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*Sponsor:* National Institute of Standards and Technology
Office of Standard Reference Materials

**OBJECTIVE** To determine the feasibility of developing a low cost aerosol concentration standard based on nebulizing a suspension of 0.1 μm diameter polystyrene spheres.

**PROBLEM** Particle contamination is a significant cause of defects in the production of integrated circuits. There is no agreed upon standard for the number concentration calibration for optical particle counters. A major application of these counters is to monitor particle contaminants in facilities where integrated circuits are assembled. Factors of two difference in number concentration measured by two instruments for the same aerosol are not uncommon. Particles of 0.1 μm size are of most interest because they represent the limit of sensitivity of most currently available counters.

**APPROACH** BFRL's research in FY 1991 focuses on determining the feasibility of developing an accurate aerosol concentration standard. The work is concerned with the long term stability of the low concentration polystyrene spheres. This effort will involve diluting the Standard Reference Material 1693, 0.1 μm polystyrene latex spheres in suspension, with ultra pure water in particle free containers. Researchers will consult with others familiar with handling particle free liquids for guidance about selecting water and containers. The particle concentration will be monitored several times during the year for stability and presence of agglomerates and mold. BFRL also will address the ability of a pneumatic nebulizer to meet the following performance requirements:

1. Capability to generate a constant aerosol concentration of 0.1 μm spheres for at least one hour,

2. Repeatability of concentration output day after day, and

3. Ease of operation so that other users obtain the same concentration.

A number of systems will be evaluated in regard to these performance requirements including the system assembled at NIST for the 0.1 μm SRM work and the Thermal Systems Inc. (TSI) Nebulizer System. We shall attempt to rent the Japan

Synthetic Rubber (JSR) Aeromaster System, which claims to produce a constant aerosol output and to be highly repeatable. This research will determine the feasibility of developing a low cost aerosol concentration standard based on nebulizing a suspension of 0.1 μm diameter polystyrene spheres. This generator would be intended as a secondary standard with a concentration accuracy of about ±10%. As soon as this generator is developed, BFRL will expeditiously transfer the results to the aerosol measuring industry which will incorporate the generator into emerging calibration standards for optical particle counters used for monitoring particle contamination in clean rooms.

**RECENT RESULTS**

"Use of the Electrostatic Classification Method to Size 0.1 μm SRM Particles—A Feasibility Study," *Journal of Research*, National Institute of Standards and Technology 96:2, March/April 1991.

Demonstrated feasibility of using electrostatic classification for sizing 0.1 μm spheres.

Used electrostatic classification to size and certify 330 bottles of 0.1 μm diameter polystyrene spheres for Standard Reference Material 1963.

## SOOT FORMATION AND EVOLUTION

*Principal Investigator:* Kermit C. Smyth
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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE**

To develop scientifically sound principles, metrology, data, and predictive methods for the formation and evolution of smoke components in flames for use in understanding and modeling general fire phenomena.

**PROBLEM**

Needed is an improved understanding of the chemical and physical processes which underlie macroscopic fire phenomena including the development of new techniques and methods for studying these processes.

**APPROACH**

Detailed flame structure measurements (species concentrations, temperature, and velocity) have been made in a laminar methane/air diffusion flame using a variety of laser-based optical techniques as well as mass spectrometric sampling. These measurements include the first quantitative results for the important OH radical and relative profiles of O atom, H atom, CH, and $CH_3$ radicals. This database is the most complete and comprehensive now available for any hydrocarbon diffusion flame. Production and destruction rates for intermediate hydrocarbons have been determined to elucidate the key pathways for chemical growth. Experiments have also investigated fuel structure effects by the addition of small amounts of ethylene, butadiene, and toluene to the base methane flame.

During 1991, BFRL is concentrating on comparing these diffusion flame experimental measurements with detailed flame structure computations of Smooke at Yale University. BFRL will then test Bilger's and Peters' reduced 4-step oxidation mechanisms against our diffusion flame results. These studies will help to establish the best approach for choosing the appropriate chemical libraries to incorporate into a model of a turbulent vortex. We are also evaluating

the major uncertainties which now exist in models of soot formation and smoke production. First order estimates of combustion-generated smoke yields will be made from a review of existing models and data. In the future, we will add appropriate reduced mechanisms for soot inception, growth, and oxidation to an overall model of soot formation and smoke production.

Research is also underway in a combined experimental and theoretical effort that is focussed on characterizing the optical properties of smoke agglomerates. The theoretical effort has consisted of generating simulated smoke agglomerates of various sizes and then computing the light scattered by the agglomerates using Rayleigh-Debye scattering theory. To study the optical properties of smoke, a transmission cell-reciprocal nephelometer has been developed. This device allows the simultaneous measurement of the extinction coefficient and the total scattering coefficient of smoke. These are the key quantities needed for studying radiation transport through a smoke cloud. This year the transmission cell reciprocal nephelometer will be validated by comparing model predictions with measurements made on a variety of scatterers.

**RECENT RESULTS**


Koseki, H. and Mulholland, G. W., "The Effect of Diameter on the Burning of Crude Oil Pool Fires," *Fire Technology*, V. 27, p. 54, 1991.

Smyth, K. C., Tjossem, P. J. H., Hamins, A., and Miller, J. H., "Concentration Measurements of OH· and Equilibrium Analysis in a Laminar Methane/Air Diffusion Flame," *Combustion and Flame*, V. 79, p. 366, 1990.

Smyth, K. C., and Tjossem, P. J. H., "Radical Concentration Measurements in Hydrocarbon Diffusion Flames," *Applied Physics B* V. 50, p. 499; special issue on Laser Diagnostics in Combustion, 1990.

Hamins, A., Anderson, D. T., and Miller, J. H. "Mechanistic Studies of Toluene Destruction in Diffusion Flames," *Combustion Science and Technology* V. 71, p. 175, 1990.

Smyth, K. C. and Tjossem, P. J. H., "Signal Detection Efficiency in Multiphoton Ionization Flame Measurements," *Applied Optics*, V. 29, p. 4891, 1990.

Benner, B. A., Bryner, N. P., Wise, S. A., and Mulholland, G. W., "Polycyclic Aromatic Hydrocarbon Emissions from the Combustion of Crude Oil on Water," *Environmental Science and Technology*, V. 29, p. 1418, 1990.

Tjossem, P. J. H. and Smyth, K. C., "Multiphoton Excitation Spectroscopy of the $B^1\Sigma^+$ and $C^1\Sigma^+$ Rydberg States of CO," *Journal of Chemical Physics*, V. 91, p. 2041, 1989.

Meakin, P., Donn, B., and Mulholland, G. W. "Collision between Point Masses and Fractal Aggregates," *Langmuir*, V. 5, p. 510, 1989.


**GRANTS**

*"Soot Morphology and Radiation in Turbulent Flames,"* Richard A. Dobbins, Brown University.

*"Simplification of Diffusion Flame Chemistry: A Theoretical and Experimental Study of the Structure of Laminar Diffusion Flames,"* J. Houston Miller, George Washington University.

*"Fundamental Mechanisms for CO and Soot Formation in Diffusion Flames,"* Robert J. Santoro, Pennsylvania State University.

*"Modelling of Soot Formation in Diffusion Flames,"* Ian Kennedy, University of California at Davis.

# FIRE HAZARD ANALYSIS

# FIRE HAZARD ASSESSMENT METHODOLOGY

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*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To produce a fundamental capability to analyze the hazards associated with a specified fire scenario.

**PROBLEM** Each year in excess of 123 billion of dollars are spent to protect occupants and equipment against fire and fire related damage and loss. In spite of the increased spending, over 6000 people die annually, and there is 600 million dollars in direct costs. To ameliorate these problems, a systematic approach to understanding the effect of fires in buildings is necessary. The fundamental capability has been provided in the form of a fully-supported software package for personal computers. While initially limited to residential-style occupancies, the software design is aimed at an across the board use of a broad range of applications from fire safety education to fire reconstruction.

**APPROACH** BFRL developed the software HAZARD I, predicts the hazard to a building and to occupants any where within the building. The next release of HAZARD I, version 1.1, will include new phenomenon and features to continue providing a state-of-the-art tool for hazard analysis for use by fire protection professionals.

The resulting product will provide a predictive tool for manufacturers, purchasers, architects, fire protection engineers, code officials, and practitioners to evaluate safety performance, code equivalency, and code change proposal issues. The fire hazard assessment methodology embodied in the HAZARD I software provides a vehicle which state-of-the-art fire science can be applied to improve fire safety. Continued enhancement of its capabilities and validity is a primary aspect to the mission of BFRL's fire program.

During 1991, BFRL will plan the direction and content of HAZARD II. These include four areas: fire model, egress and tenability models, databases, and user interface/documentation.

**RECENT RESULTS**

Peacock, R. D. and Bukowski, R. W., "A Prototype Methodology for Fire Hazard Analysis," *Fire Technology*, 26:1, 15-40, February 1990.

Peacock, R. D., and Babrauskas, V., "Analysis of Large-Scale Fire Test Data," *Fire Safety Journal* (in press).

Peacock, R. D., Breese, J. N., and Forney, C. L., *A Users Guide for RAPID, Version 2.3*, NIST Spec. Publ. 798, October 1990.

Peacock, R. D., Davis, S., and Forney, C. L., *Data for Room Fire Model Comparisons*, NIST Special Publication, to be printed 1991.

**GRANTS** *"Modifications to Furniture Fire Model for HAZARD System,"* M. A. Dietenberger, University of Dayton Research Institute.

*"Mathematical Modeling of Human Egress from Fires in Residential Buildings,"* M. Kostreva, Clemson University.

*"Incorporating Convective and Radiative Heat Transfer into the Code CCFM.VENTS,"* W. F. Moss, Clemson University.

*"Fire Risk Analysis Methodology,"* G. Apostolakis, University of California at Los Angeles.

## FIRE RISK ASSESSMENT

*Principal Investigator:* Walter W. Jones
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301.975.6887

*Sponsor:* National Fire Protection Research Foundation

**OBJECTIVE** To provide users of the BFRL fire risk assessment methodology with software and documentation to use the software.

**PROBLEM** An important application of fire models is to predict the fire effect of furnishings on occupants. Building decision makers need a technique that assesses the effect of changing room furnishings on the hazard to occupants.

**APPROACH** During FY 1991, BFRL will develop a user guide for implementing the BFRL fire risk assessment software on a Concurrent Computer, and a computer tape which contains the source for the implementation. This work consists of two tasks. The first is to create ports for the Risk Assessment Software to at least one other platform and to adapt the software so it's operational on the PC line of computers.

The second is to aide users to develop the necessary files for other scenarios than provided in the documentation. This involves developing a report which describes the software in task 1, and operational guidelines. The guidelines will include a sample calculation. To the extent possible, the code will be annotated, and directions given, to indicate where system specific information exists, and how it could be modified. The directions will facilitate its transfer to other computers, such as a DEC Vax.

This quantitative risk prediction methodology offers new techniques to evaluate the contribution of specific materials and products to fire risk in specified occupancies.

**RECENT RESULTS** Forney, C. L. and Jones, W. W., *Fire Risk Assessment Method: Guide to the Risk Methodology Software*, NISTIR 4401, 1990.

## FIRE AND SMOKE SPREAD IN SHIPS

*Principal Investigator:* Walter W. Jones
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*Sponsor:* Department of the Navy
Naval Research Laboratory

**OBJECTIVE** To provide data analysis, predictive capability, display and data acquisition in support of full scale fire testing on the ex USS SHADWELL.

**PROBLEM** A systematic approach to understanding the effect of fires in compartmented structures is necessary to maintain a high level of use and confidence in the fire growth and smoke transport model published by BFRL. It is necessary to assure the correctness of the model and to incorporate the most complete physical phenomenology available.

**APPROACH** In FY 1991 and 1992 BFRL will enhance the model and develop derivative modules specific to Navy applications. As part of the validation and verification process, the data obtained in full scale test on the SHADWELL will be analyzed and compared with the CFAST model.

During FY 1991, BFRL will implement the most recent version of CFAST on the Navy minicomputer based on the ex USS SHADWELL. This will include mechanical ventilation, hydrogen chloride deposition, vertical flow and display of the results in real time. Included in the model will be the capability for calculating vitiated combustion, hypergolic and rocket fuels and class A materials.

BFRL's work involves three Tasks:

1. Install version 1.0 of CFAST in the Masscomp (Concurrent) Computer on the ex USS SHADWELL. Version 1.0 includes mechanical ventilation, ventilation controlled and unconstrained fires, and hydrogen chloride deposition.

2. Perform a series of calculations to determine the effects of ventilation, structural damage (breaking bulkheads) and various fuels in the context of shipboard fires. The data sets to perform these calculations will be installed on the shipboard computer.

3. Assist NRL install and commission the data files to run the computer model for these configurations while BFRL performs these experiments onboard the ex USS SHADWELL.

The results of this research will provide the U.S. Navy with the capability to calibrate experiments for improved testing efficiency. Graphical display capabilities will provide enhanced experimental visualization.

**RECENT RESULTS** Installed the CFAST model and associated support programs on the ex USS SHADWELL.

Developed a planning version of a real time display for experimental visualization and damage control management.

# FIRE TOXICITY MEASUREMENT

## TOXIC POTENCY MEASUREMENT

*Principal Investigator:* Vytenis Babrauskas
Fire Measurement and Research Division
301.975.6679

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE** To provide a rational and practical system for obtaining accurate toxic potency data for hazard models and product evaluation and to predict toxic effects of fire gases on rodents and humans.

**PROBLEM** A test method is needed to evaluate the toxic potency of smoke from materials which is applicable to humans and minimizes use of animals.

**APPROACH** The focus of BFRL's research during FY 1991 is on the development of validation hypotheses to predict fire hazards from test data. Research focuses on developing a bench-scale radiant heat toxicity apparatus. In cooperation with SwRI, BFRL is developing a test protocol as an improvement on existing methods to better test composite specimens. Work continues in setting up a computational model for CO production and elimination to correctly predict rat and human responses. This work is scheduled for completion at the end of FY 1991.

BFRL also is working toward the completion of a consolidated presentation of the N-Gas model. Work continues on determining the non-linear interaction between $NO_2$ and HCN effects and incorporating HCl into the model.

**RECENT RESULTS**

Babrauskas, V., Harris, R. H., Jr., Braun, E., Levin, B. C., Paabo, M., and Gann, R. G., "Large-Scale Validation of Bench-Scale Fire Toxicity Tests," pp. 3–12, *INTERFLAM '90*, Fifth International Fire Conference Proc., London (1990).

Levin, B. C. and Gann, R. G., "Toxic Potency of Fire Smoke: Measurement and Use," *Fire and Polymers—Hazards Identification and Prevention*, edited by G. L. Nelson, ACS Symposium Series 425, American Chemical Society, Washington, DC, pp. 3–11, 1990.

Braun, E., Gann, R. G., Levin, B. C., and Paabo, M., "Combustion Product Toxic Potency Measurements: Comparison of a Small-Scale Test and 'Real-World' Fires," *Journal of Fire Sciences* 8:63–79, 1990.

Levin, B. C., Paabo, M., Highbarger, L., and Eller, N., *Synergistic Effects of Nitrogen Dioxide and Carbon Dioxide Following Acute Inhalation Exposures in Rats*, NISTIR 89-4105, June 1989.

**GRANTS**

*"Laboratory Smoke Evolution Studies Using the SwRI Radiant Combustion/Exposure Apparatus,"* Arthur Grand, Southwest Research Institute.

*"Toxicity of Plastic Combustion Products,"* Yves Alarie, University of Pittsburgh.

*"Analysis of Hazards to Life Safety in Fires: A Comprehensive Multi-dimensional Program, Part IV"* (work from FY 89), Walter G. Switzer, Southwest Research Institute.

## CONE CALORIMETER DEVELOPMENT

*Principal Investigator:* Vytenis Babrauskas
Fire Measurement and Research Division
301.975.6679

*Sponsor:* National Institute of Standards and Technology

**OBJECTIVE**

To develop an improved method to measure heat, smoke, soot, mass, and combustion gas release rates and related quantities (ignition time, heat of combustion).

**PROBLEM**

The Cone Calorimeter standard was issued by three standards organizations during FY 1990. The standards are similar, but not identical. The ASTM standard is the most general and complete. The ISO standard is essentially identical but excludes, for jurisdictional reasons, the sections dealing with the measurement of smoke. The NFPA standard is oriented specifically towards the testing of furniture composites.

During FY 1990 BFRL performed work in three areas: 1) held Cone Calorimeter round robins for ASTM and ISO; 2) organized Cone Calorimeter Workshops; and 3) provided assistance to users. For the three U.S. standards organizations a separate roundrobin was held for each. Data were compared from previous round robins for reaction-to-fire test methods, results showed BFRL's round robins produced better results than comparable data from previous methods. Three Cone Calorimeter Workshops were organized under the auspices of the International Heat Release Association: two in the United Kingdom and one in United States.

**APPROACH**

During FY 1991, BFRL will participate in standards development work to further disseminating the capabilities of BFRL's Cone Calorimeter and will continue assisting users by conducting a series of workshops and conferences.

**RECENT RESULTS**

Mulholland, G., Janssens, M., Yusa, S., and Babrauskas, V., "The Effect of Oxygen Concentration on CO and Smoke Produced by Flames," *Fire Safety Science—Proc. of the Third International Symposium*, 1991.

Babrauskas, V., and Peacock, R. D., "Heat Release Rate—The Single Most Important Variable in Fire Hazard," *FRCA Fall Meeting Proceedings*, 1990.

Babrauskas, V., "Modern Test Methods for Flammability, Recent Advances in Flame Retardancy of Polymeric Materials," Business Communications Co., Norwalk, CT, 1990.

Babrauskas, V., *Modern Test Methods for Flammability, Recent Advances in Flame Retardancy of Polymeric Materials*, NISTIR 4326, 1990.

Ryan, J. D., Babrauskas, V., O'Neill, T. J., and Hirschler, M. M., "Performance Testing for the Corrosivity of Smoke," pp. 75–88, *Characterization and Toxicity of Smoke* (STP 1082), American Society for Testing and Materials, Philadelphia, 1990.

Babrauskas, V., "The Cone Calorimeter—A New Tool for Fire Safety Engineering," *ASTM Standardization News*, 18, 32–5, January 1990.

Babrauskas, V., "New Test Methods for Assessing Smoke, Toxic Products, Corrosive Products, and Heat Release in Fires," pp. 20–33, *Flame Retardants '90*, The British Plastics Federation, ed., Elsevier Applied Science, London, 1990.

Babrauskas, V., "Flammability of Upholstered Furniture with Flaming Sources," *Cellular Polymers* 8, 198–224, 1989.

## COMPUTATION-AIDED DESIGN OF FIRE-RESISTANT POLYMERS

***Principal Investigator:*** Marc R. Nyden
Fire Measurement and Research Division
301.975.6692

***Sponsor:*** National Institute of Standards and Technology

**OBJECTIVE** To establish a technical basis for computer-aided design of flame-resistant materials which retain their intended-use properties and do not show increased smoke toxicity.

**PROBLEM** Concerns ranging from global competitiveness to public safety are placing demands on manufacturers of materials. As standards for acceptable performance become more numerous and complex, the traditional trial and error approach to materials design becomes at the same time, more expensive and less successful.

**APPROACH** Thermal degradation is the first step in the combustion of solids. An efficient route to improving fire resistance is to affect a change in the degradation chemistry of the material to promote the formation of a char and inhibit the formation of volatile fuel. BFRL is pioneering a new approach to the design of fire-resistant materials which uses experimentally determined kinetic and flammability data to calibrate a molecular dynamics model of polymer degradation.

During FY 1991, BFRL is numerically modeling and systematically varying complex materials (are expensive to synthesize in the laboratory) to identify structural features and/or additives which reduce flammability. Computer simulations suggest that free radical initiators and metallic catalysts are char promoters in polyethylene. This suggests they may be effective as flame retardants.

**RECENT RESULTS** Nyden, M. R. and Noid, D. W., "Molecular Dynamics of Initial Events in the Thermal Degradation of Polymers," *Journal of Physical Chemistry* 95, 940, 1991.

Blaisten-Barojas, E. and Nyden, M. R., "Molecular Dynamics Study of the Depolymerization Reaction in Simple Polymers," *Chemical Physics Letters* 171, 499, 1990.

Nyden, M. R., "Computer Simulations of Thermal Degradation in Polymers," *Polymer Preprints*, 30, 98, 1989.

## COPPER INTERACTIONS WITH FIRE GASES

*Principal Investigator:* Barbara C. Levin
Fire Measurement and Research Division
301.975.6682

*Sponsors:* International Copper Association, Ltd. and
The Society of the Plastics Industry, Inc.

**OBJECTIVE** To determine if the reduced levels of hydrogen cyanide (HCN) generation and resultant toxicity from copper-impregnated flexible polyurethane foams observed under small-scale laboratory conditions occurs when copper-treated materials are combusted under medium- and large-scale conditions.

**PROBLEM** The toxicity of burning flexible polyurethane foams (FPU) is often determined by the evolution of HCN. If the amount of HCN evolved can be reduced, then a reduction in the fire toxicity is expected. Previous BFRL studies have shown that FPU treated with copper dust, cupric oxide, cuprous oxide or copper sulfate produced significantly less HCN when thermally decomposed than the identical but untreated control foams. This reduction of HCN and toxicity occurred regardless of whether the copper or copper compound was added to the foam during its formulation (prior to the foaming process) or added as a post-treatment (after formulation).

During FY 1990, BFRL examined the following flammability properties in foams with and without 0.1% cuprous oxide: 1) ignitability in three systems [the NBS Toxicity Test Method, the Cone Calorimeter, and Lateral Ignition and Flame Spread Test (LIFT)], 2) rate of heat release, 3) smoke obscuration, and 4) rate of flame spread. In all cases, no differences in flammability characteristics between the treated and untreated foam were observed.

**APPROACH** During FY 1991, BFRL continues its research addressing medium (furniture calorimeter) and full-scale (room burns) tests of copper-impregnated foam cushions and examining the effect of different combustion conditions. In the first series of large-scale tests the HCN levels were not reduced by the presence of 0.1% cuprous-oxide. Continuing work will focus on determining the conditions under which beneficial results are observed.

Reduction of the toxicity of polyurethane foams through such low cost mechanisms will have a major impact on improving public fire safety.

**RECENT RESULTS**

Levin, B. C., Paabo, M., Harris, R. H., Clark, H. M., Yoklavich, M. F., Eller, N. and Highbarger, L., "The Effect of Copper Additives on Atmospheric Hydrogen Cyanide and Acute Inhalation Toxicity from the Combustion products of flexible polyurethane," *Proceedings of The Fire Retardant Chemicals Association Fall Conference*, Scottsdale, AR, October 1989, pp. 107–112.

Levin, B. C., Paabo, M., Harris, R. H., Eller, N., and Highbarger, L., "Copper Additives Decrease the Acute Inhalation Toxicity of the Combustion Products of Flexible Polyurethane by Inhibiting Hydrogen Cyanide Generation," *International Copper Association*, Annual Report, Year 2, Ltd., June 1989.

## FLAMMABILITY STANDARD FOR PRISON MATTRESSES

*Principal Investigator:* Vytenis Babrauskas
Fire Measurement and Research Division
301.975.6679

*Sponsor:* National Institute of Standards and Technology
Law Enforcement Standards Laboratory

**OBJECTIVE** To develop a bench-scale flammability standard for testing prison and jail mattresses.

**PROBLEM** Mattresses used in prisons and jails are typically purchased using prescriptive specifications that defines the composition of each component. A full-scale fire test procedure for mattresses (California T.B. 121) exists, but is not commonly used. The corrections community is concerned about two aspects of the status quo of flammability standards. The first, during prisons accreditation surveying, there are no practical means to verify if mattresses are providing a reasonable level of safety. The second, one of the most common methods of constructing prison mattresses involves use of fire retardants which are not permanent (a possibility of unrecognized degradation in use). In view of this situation, the Advisory Council to Law Enforcement Standards Laboratory (LESL) recommended that work be started on developing a bench-scale test standard.

**APPROACH** BFRL HAS contacted a wide spectrum of corrections officials to determine their views on this matter. Based on their suggestions a test development program was formulated. During FY 1991, BFRL will continue working with the state of California to develop a bench-scale flammability standard for testing prison and jail mattresses. The state of California has an on-going program where mattresses are being evaluated in their full-scale test facility. BFRL will test the same mattresses in bench-scale, using its Cone Calorimeter. The full-scale data will be used to validate the bench-scale findings. A leaching procedure will be developed to assess the permanence of the retardant treatment. Water-soluble or mechanically-separable components in the test mattresses will be leached out by this procedure prior to heat release rate testing in the Cone Calorimeter.

**RECENT RESULTS** New project 1990.

# FIRE SUPPRESSION

## FIRE SUPPRESSION

*Principal Investigator:* David Evans
Fire Measurement and Research Division
301.975.6899

*Sponsors:* Institute of Standards and Technology, and
Department of Health and Human Services
National Institutes of Health
Facilities Engineering Branch

**OBJECTIVE** To understand the fire extinguishment processes and develop techniques to measure and predict the performance of fire protection and fire fighting systems.

**PROBLEM** Lack of predictive methods for the performance of fire suppression system prevents inhibits the development of performance based standards. BFRL research in fire suppression is advancing the fundamental understanding of the performance of systems and developing a predictive capability.

**APPROACH** During 1991, BFRL is assessing the role of NIST in fire suppression research. As a result of this assessment a long range research plan is under development in consultation with experts from industry, government, and academia.

Using the results of FY 1990 studies of water spray suppression of wood crib fires, a first generation fire suppression model for use in future releases of HAZARD is being documented.

As part of BFRL's work in exploring the use of commercial Computational Fluid Dynamics codes for evaluating fire phenomena, measurements of $CO_2$ dispersion in an enclosure are being compared with computed results using the FLOW3D Code.

In a special study for the National Institutes of Health (NIH) BFRL assessed the ability of new quick response sprinkler technology to provide life safety for patient room protection using a specially constructed hospital room at NIST that matches NIH facility dimensions.

In cooperative research with the University of Maryland, the heat transfer characteristics of water droplet evaporation from hot surfaces are being studied to formulate a thermal model for extinction of burning solids.

**RECENT RESULTS**

Walton, W. D., *Quick Response Sprinklers in Chemical Laboratories—Fire Test Results*, NISTIR 89-4200, November 1989.

Notarianni, K. A., *Five Small Flaming Fire Tests in a Simulated Hospital Patient Room Protected by Automatic Fire Sprinklers*, NIST Report of Test FR 3982, October 1990.

diMarzo, M. and Evans, D. D., "Evaporation of a Water Droplet Deposited Over a Hot High Conductivity Solid Surface," *J. Heat Transfer*, Vol III, No. 1, 210, 1990.

Klassen, M., diMarzo, M., and Sirkis, J., "Infrared Thermography of Dropwise Evaporative Cooling," *Proc. Thermophys*. Heat Transfer Conf., HTD Vol. 141, 117, 1990.

BFRL provided technical support to the National Fire Protection Association to resolve difficulties with the use of model prediction for sprinkler actuation in large buildings. Field measurements of temperature conditions produced by an alcohol test fire in an aircraft hanger were used to test two different sprinkler response models developed by BFRL—DETACT and LAVENT.

**GRANTS**

*"Extinguishment of Combustible Porous Solids by Water Droplets,"* A. Atreya, Michigan State University.

*"Transient Cooling of a Hot Surface by Droplet Evaporation,"* Marino di Marzo, University of Maryland.

*"Port the Fire Demand Model to a PC Computer,"* Larry Pietrzak, Mission Research Corporation, Santa Barbara, California.

## MEASUREMENT OF CONDITIONS RESULTING FROM A SMALL FLAMING FIRE IN A SIMULATED NIH HOSPITAL PATIENT ROOM PROTECTED BY AUTOMATIC FIRE SPRINKLERS

***Principal Investigator:*** Kathy A. Notarianni
Fire Measurement and Research Division
301.975.6883

***Sponsor:*** National Institutes of Health
Division of Engineering Services

**OBJECTIVE** To generate a data bank of measured fire exposures and combustion product concentrations occurring at the patient location and activation times of various automatic sprinklers and smoke detectors.

**PROBLEM** Requirements for the installation of automatic sprinklers and/or smoke detectors in patient sleeping rooms of hospitals are being considered within the NFPA standards making process. Options available for consideration by the designer or owner include conventional sprinklers, quick response sprinklers, smoke detectors, or a combination of sprinklers and smoke detectors. Needed are data for automatic sprinklers and smoke detectors for development of selection criteria.

**APPROACH** Propane burner tests were conducted to determine the size of a small flaming fire, in terms of heat release rate, that could cause potentially harmful conditions in a patient room. 60 kw was determined to be the critical fire size.

Burns of various fuel packages were conducted under a calorimeter in order to identify a package with a nominal 60 kw rate of heat release. This was determined to be a wood crib approximately 460 mm × 610 mm × 15 mm high (18×24×6 in), weighing about 7.7 kg (17 lbs).

A series of five full-scale fire tests were conducted to measure temperatures, radiation, and carbon dioxide, carbon monoxide, and oxygen concentrations resulting from the flaming wood crib fires within the simulated NIH Clinical Center

Hospital room protected with automatic sprinklers. Activation time of quick response and standard response sprinklers and ion and photoelectric smoke detectors at various locations in the room were recorded. A final report will be published in July 1991. The results from this study will help NIH assess what system(s) is required to ensure adequate, cost effective fire protection in their hospital patient rooms.

**RECENT RESULTS**

Notarianni, K. A., *Five Small Flaming Fire Test in a Simulated Hospital Patient Room Protected by Automatic Fire Sprinklers*, NIST Report of Test FR 3982, October 1990.

## THE DEVELOPMENT OF SPRINKLER EFFECTIVENESS METHODOLOGY FOR THE GSA ENGINEERING FIRE ASSESSMENT SYSTEM

*Principal Investigator:* Daniel Madrzykowski
Fire Measurement and Research Division
301.975.6677

*Sponsor:* General Services Administration
Public Buildings Service
Office of Real Property Management and Safety

**OBJECTIVE**

To acquire data on heat release rates for GSA's fire hazard assessment system and develop the methodology to incorporate sprinkler effectiveness into the system.

**PROBLEM**

BFRL has developed an engineering fire hazard assessment system (FPETOOL) to evaluate hazard and fire protection strategies in GSA buildings. Although FPETOOL can be used to evaluate a wide range of conditions, it does not specifically address fire suppression.

**APPROACH**

Thirty large scale fire tests were performed under an oxygen consumption calorimetry hood to determine the heat release rate (HRR) of fuel packages with and without sprinklers. Fuel packages included work stations, office furnishings, paper recycling hampers and wooden cribs. Each fuel package was tested under free burn conditions to obtain HRR curves.

The HRR measurements were repeated individually to determine the effect of water spray. The sprinkler was manually activated when the HRR of the fuel package was between 90- and 100% of its free burn peak HRR. The average water spray density over the fuel package floor area was 4.07 mm/min (0.1 gpm/ $ft^2$)

To arrive at the sprinkler effectiveness methodology, the heat release rates measured during suppression were divided by their respective free burn heat release rates. This yielded normalized values for the reduction of HRR for all of the fuel packages. A first order sprinkler effectiveness curve was constructed by determining the maximum normalized HRR, from all of the tested fuel packages, for the 10 minute period after sprinkler activation. Further testing will be performed in FY 1991 to evaluate the limitations of these results as a basis for a sprinkler effectiveness methodology for use in FPETOOL. The results of these sprinkler tests are intended to provide a basis for fire suppression prediction in FPETOOL. A final report will be published in the summer 1991.

**RECENT RESULTS**

New project in 1990.

## SAFETY IN OFFSHORE DRILLING

*Principal Investigator:* David Evans
Fire Measurement and Research Division
301.975.6899

*Sponsors:* U.S. Department of Interior
Minerals Management Service
Technology Assessment and Research Branch

American Petroleum Institute
Health and Environmental Department

Department of Transportation
U.S. Coast Guard
Research and Development Center

**OBJECTIVE** To examine technologies that can mitigate the effects of oil spills and fires from offshore platform accidents.

**PROBLEM** Blowout fires and oil spills represent a safety and environmental threat associated with accidents in offshore drilling operations. The use of water sprays to cool blowout fires and the use of controlled burning to remove oil spills from the water are possible means to mitigate the effects of these accidents. New technology would provide industry with additional means to enhance the safety of offshore drilling operations.

**APPROACH** Research in 1991 concentrates on building and evaluation of instrumentation for sampling combustion products from large scale fires of the size that would be used to burn oil released from accidents on offshore platforms. Recent interest in the application of burning as a response to oil spills from transportation accidents has accelerated the program of research and included the opportunity to test equipment in 15 meter diameter crude oil fire tests being conducted in cooperation with the U.S. Coast Guard Fire Test Detachment in Mobile, AL. Measurement of soot generation from laboratory crude oil fires tests at BFRL and the Fire Research Institute in Japan are used to predict downwind dispersion and deposition of smoke particulate from large scale fires. This work involving the development of new calculation methods for buoyant plume flow is performed in cooperation with researchers at the Massachusetts Institute of Technology. Information from this study is expected to be critical to gain acceptance for the use of burning as an option in oil spill response.

Analysis of the effects of water spray on jet-flames associated with high pressure releases of both liquid and gaseous hydrocarbons is being studied in a cooperative BFRL and University of Maryland project. Several aspects of the oil and gas well blowout and diverter fires are being addressed. These include: 1) predicting radiative heat fluxes from natural gas jet flames spanning heat release rates from 10 kW to 200 MW; 2) demonstrating the efficacy of water in controlling the radiation loading and suppressing the fire with water injected from near the well head; 3) developing extensions to treat the two phase, two fuel aspects of oil well blowout fires; and 4) predicting horizontal flame trajectories as a basis for analysis of diverter fires.

**RECENT RESULTS**

Evans, D., Mulholland, G., Lawson, J., Tennyson, E., Tebeau, P., Fingas, M., Gould, J., "Burning of Oil Spills," *Proceedings of the 1991 International Oil Spill Conference—Prevention, Behavior, Control, Cleanup,* San Diego, CA, March 4–7, 1991.

Evans, D., Walton, W., Baum, H., Lawson, R., Rehm, R., Harris, R., Ghoniem, A., and Holland, J., "Measurement of Large Scale Oil Spill Burns," *Proceedings of the Thirteenth Arctic and Marine Oil Spill Program Technical Seminar*, Edmonton, Alberta, Canada, June 6–8, 1990.

Benner, B., Bryner, N., Wise, S., Mulholland, G., Lee, R., and Fingas, M., "Polycyclic Aromatic Hydrocarbon Emissions from the Combustion of Crude Oil on Water," *Environmental Science and Technology*, Vol. 24, 1990.

Gore, J., Skinner, S., Stroup, D., Madrzykowski, D., and Evans, D., "Structure and Radiation Properties of Large Two Phase Flames," *Heat Transfer in Combustion Systems*, (N. Ashgriz, J. Quintiere, H. Semerjian, and S. Slezak, eds.) HTD-Vol. 122, ASME, New York, 1989.

Developed instrumentation packages for measuring soot yield (fraction of fuel burned emitted as soot), particulate concentration, combustion product composition for use in large scale field tests.

Completed measurements of soot yield and burning rate on 3 m diameter crude oil fires using newly developed equipment at the fire Research Laboratory in Japan.

Completed measurements of soot yield from 15 m diameter fuel oil burns. These measurements are the first known data on soot yield from large fires.

Completed a new plume flow analysis method based on vortex element models for calculating soot particulate deposition downwind of a large fire.

Demonstrated the scaling capabilities of laminar flame model which represents turbulent flames as wrinkled laminar flames by successfully calculating the radiation heat flux from methane air flames with heat release rates in the 1–10 MW range.

The effect of water spray on temperature and radiation from methane jet flames was calculated with mixed success using effective properties of the two phase mixtures under the assumption of local thermodynamic and fluid mechanical equilibrium. The analysis predicts the decrease in temperature reasonably well. However, the effect of flame radiation was overestimated. the effects of lack of fluid mechanical equilibrium between the gaseous and liquid phases are being investigated as a cause of this discrepancy.

**GRANTS**

*"A Study of Pool Combustion of Crude Oil Supported on Water,"* K. Saito, University of Kentucky.

*"An Investigation of Simulated Oil Well Blowout Fires,"* J. P. Gore, University of Maryland.

*"Numerical Modeling of Plume Dispersal and Smoke Deposition from Large Scale Fires,"* A. Ghoniem, Massachuetts Institute of Technology.

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In early 1991, as part of an agency-wide reorganization, the National Institute of Standards and Technology (NIST) created the Building and Fire Research Laboratory (BFRL) by merging its Centers for Building Technology and Fire Research. BFRL's mission is to increase the usefulness, safety, and economy of constructed facilities, and reduce the human and economic costs of unwanted fires in buildings.

This report summarizes BFRL's research for 1991. The report is arranged by its research programs: structural engineering, materials engineering, mechanical and environmental systems, fire science and engineering, and fire measurement and research. Each summary lists the project title, its research, the BFRL point of contact, sponsor, and results.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

building controls, building research, coatings, combustion and flammability, computer integrated construction, concrete, earthquake engineering, fire dynamics, fire hazard, fire physics, fire safety, heat and moisture transfer, indoor air quality, lighting, quality assurance laboratories, refrigeration, smoke dynamics, structural performance, suppression, test procedures, toxicity

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